MALLEABLE IRON

CASTINGS

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PREFACE

The Malleable Founders Society, in 1944, published a book which at the time was perhaps the most comprehensive and authoritative treatise available on the subject of malleable iron.

This book, entitled "American Malleable Iron—A Handbook," had a very favorable reception and has been recognized since as an outstanding general reference source in its field.

In the intervening years since the Handbook was published, there have been many changes in the malleable industry. Research has broadened our scientific knowledge, new manufacturing methods have been introduced, and more efficient production equipment has been developed, all resulting in better products and wider product acceptance.

To reflect all of this prompted a new edition of the Handbook. But the modifications were so extensive that a simple revision would not do. An entirely fresh start had to be made. Consequently, all chapters of this present book have been entirely rewritten so as to incorporate that which is new and to reflect the myriad changes in the malleable castings art.

The book has been very carefully edited, is pertinently illustrated, and contains the results of certain research work conducted primarily for inclusion here. Carefully selected data graphs, engineering and other tables, an extensive bibliography, and comprehensive indexing will insure this publication's effectiveness as a reference.

In sum, every effort has been made to make the book accurate, complete, and up-to-date in every respect. Though written for a diversified and sometimes technical readership, even the casual reader will find much of interest in the narrative chapters and elsewhere.

Grateful appreciation is expressed to the many individuals, committees of scientific groups, the members of the Malleable Founders Society and its staff, and the others who have given so freely of their time and effort to make this book possible.

The industry is especially indebted to the following members of the Handbook Committee, whose tireless efforts through many months are primarily responsible for this volume:

HARVEY E. STEINHOFF, *Chairman,* Wagner Castings Company
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HANS J. HEINE, *Secretary,* Technical Director, MFS

The assistance of JAMES H. LANSING, former technical director of Malleable Founders' Society, and FRED G. FASSETT, JR., former editorial consultant, is acknowledged.

If the book may serve to promote an ever-increasing knowledge of malleable and pearlitic malleable irons and an ever-expanding use of these metals in our American economy, its sponsors will feel very well-rewarded.

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* Deceased.

The Malleable Founders Society expresses its appreciation to the many members and friends who so graciously cooperated in supplying illustrative material.

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I

HISTORY OF MALLEABLE IRON

MALLEABLE iron is a cast alloy consisting principally of iron and carbon which is rendered tough and ductile by a controlled heat-conversion process. Because of its unique metallurgical structure, it has the valuable properties of strength, great toughness, remarkable resistance to heavy and repeated impact, excellent ductility, high resistance to corrosion, and easy machinability. Its versatile castability makes possible sound castings, accurate to pattern, in complicated as well as simple forms, over an extensive range of weights and sizes. The combination of these properties in this one metal has established it as the ideal material for a wide diversity of applications. In fact, malleable iron castings as we know them today solve the dilemma posed in the old saying that "wrought iron cannot be cast and cast iron cannot be wrought." A glance at the history of ironmaking will make this plain and will contribute to understanding how and why malleable iron attains its properties.

The first use of iron is lost in the mists of prehistoric time. It is clear that primitive man learned that heating a type of reddish earth would give him a red hot mass of material which he could pound into shapes of his own design. The reddish earth was iron ore—oxides of iron. The wood fire which heated it formed charcoal. This served as the reducing agent to deoxidize the ore, leaving essentially pure iron which could be "worked" or "wrought."

In later recorded time, the ore was reduced in Catalan hearths,* as shown in Fig. 1, and then in their successors, the early stack furnaces. In these, temperatures were sufficient to produce only an incandescent spongy mass of iron. The metal, however, was almost pure chemically, for two principal reasons: First, the temperatures were still below the

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* See Glossary for definitions.

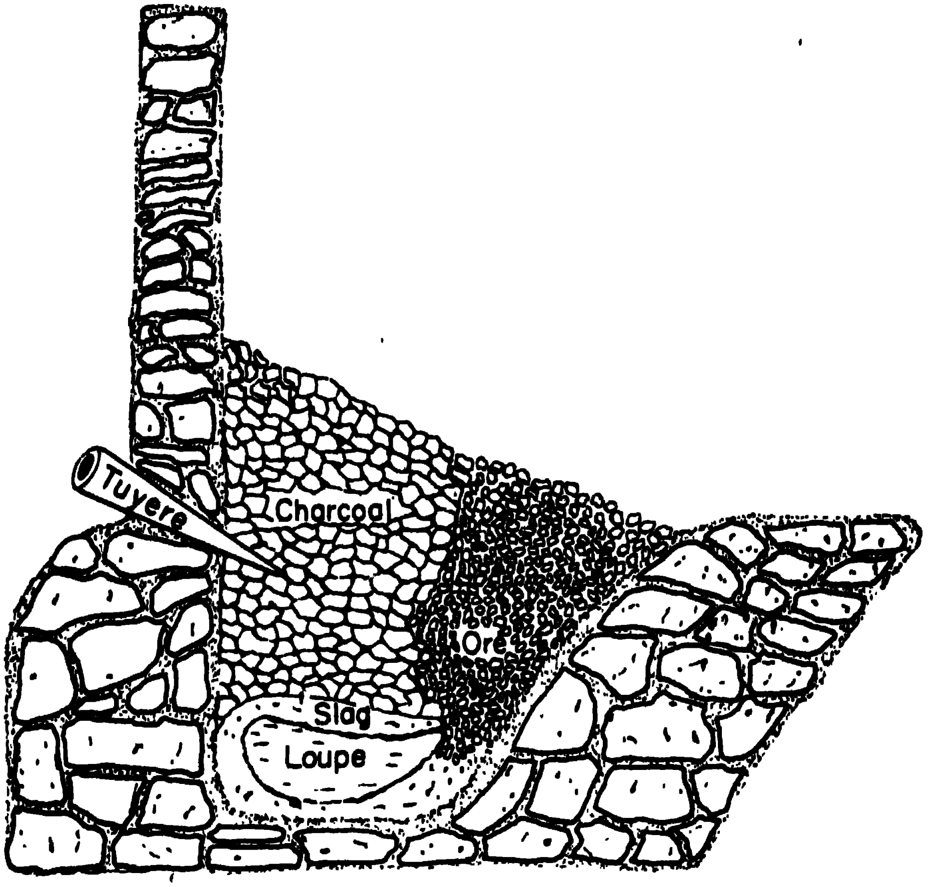


Fig. 1. **Cross-section of a Catalan hearth as used by the Moors in Spain. Ore and charcoal were charged vertically. Iron in pasty condition formed a loupe shielded by slag.**

ranges where chemical combination could occur between the iron and any other elements present—notably the carbon of the charcoal; and, second, at the temperatures attainable the charcoal ash, resulting from combustion of the fuel, sintered or partially fused with the clay and other minerals found in nature with the ore, to form a slag. Some of the slag worked through and out of the hot mass, but because the iron was pasty in texture, much slag remained entrapped. The glowing masses with which the early iron masters worked were known as "blooms," and their furnaces as "bloomeries," which in their later built-up forms became the "high furnaces" of Renaissance Europe and were the forerunners of the modern cupola and blast furnace. The blooms were forged by hammering, to shape and form the articles desired, and to force out as much as possible of the entrapped slag.

Improvements in furnaces and their performance led in time to complications; the iron produced became more difficult to work and when cooled it lacked strength and could easily be broken. Reheating the iron, some of the early ironworkers found, at least partially restored the more ductile conditions they thought of as natural. This rule-of-thumb technique relied on the basic chemical principle that with sufficient temperature carbon will migrate in iron. If the carbon content is higher in the materials or atmosphere surrounding the iron than in the iron itself, carbon will enter and migrate through the iron; if the carbon content is higher in the iron, it will migrate toward the surface and out of the iron. The first process—absorption of carbon—is called carburization; the second—removal of carbon—is decarburization. During carburization, carbon combines with iron to form iron carbide, harder and more brittle than pure iron. Decarburization frees carbon from the carbide, restoring the iron to a chemically purer, softer state.

Up to this time the iron obtained by the *direct* reduction of the original ore could be wrought, for the temperatures had not been high enough to cause any appreciable carburization. Now the higher temperatures provided by improved furnaces had introduced the hardening influence of carbon into ironmaking. As the ore was reduced with charcoal at these more elevated temperatures, the carbon-rich fuel and its gases of combustion supplied the excess carbon that carburized the formerly pure iron of the blooms, making it hard and unworkable. It therefore became necessary to go to the *indirect* or two-stage process of first producing a carburized hard bloom by reduction of ore, and then by a heat-treatment decarburizing it to prepare it for ultimate forging. When the hard blooms were reheated, preparatory to being formed into desired shapes, much less fuel was needed than that required in the original reduction of the ore, and so the furnace atmosphere was now decarburizing in nature. Hence the carbides were partially broken up, carbon migrated out of the iron, and the iron was chemically repurified, its hardness lowered, and its workability restored.

As the height of the ancient stack furnaces increased, the time of contact between ore and charcoal lengthened, temperatures grew hotter and carbon absorption increased. Ironmasters, who now were making blooms so large that they were unwieldy and had to be pulled apart into pieces of convenient size for forging, were beginning to hope that finally they would be able to melt iron and cast it as other metals were cast. The blooms, they expected, would soften progressively and ultimately liquefy. The time came in the first decade of the fourteenth century when, in some furnace, well before seemingly high enough temperatures were reached, iron actually melted. Breaking into this furnace for the removal of the expected bloom, the ironworkers found that the fluid metal had run down into the furnace hearth, collected into a molten pool, and rid itself of the lighter slag, which floated on the surface. The now well-known capacity of carbon for lowering the melting point of iron had come into play and had produced an iron rich in hard iron carbide, but relatively slag-free and clean.

The introduction of melting had several profoundly important effects. Since working out slag during forging now became almost unnecessary, the indirect process proved to be more efficient and economical *than the direct, which involved both* a *much longer reduction period* at lower temperatures to avoid carburization and then laborious forging to drive out the slag. Melting, therefore, was the greatest single influence in the adoption of the indirect process, which became general practice during the fourteenth century. Moreover, once molten iron was available, coupled with experience in the casting of other metals, iron founding was at hand. Castings made of the newly available material had to be confined to a limited field, since they were of a highly carburized iron, and therefore very hard and brittle. The advent of molten iron, too, permitted a time lag in the progression from raw material to finished product, through the device of running the molten metal out of the furnace into shallow, thinly connected troughs to cool into pieces that were easily broken apart. The troughs, when filled, had a most realistic resemblance to a sow with suckling pigs, hence the term "pig iron." For the infant foundry industry of this period, with meager demand for its brittle, hard castings, relatively little melting stock was necessary. Of the two means for obtaining it—the direct reduction of ore or the melting of pig iron—the second was clearly cheaper and more practical and was adopted where possible, thus contributing further to the establishment of the indirect process. No significant amount of gray iron, malleable iron, or cast steel is made today by a process deriving its basic iron direct through the reduction of ore.

The time when iron was first melted is, clearly, a key date in the history of an industry that is vital to Western civilization. At that point two contrasting materials had been evolved: The first was wrought iron—strong, durable, and ductile in proportion to its freedom from carbon and slag, but, because of the necessary forging with crude and clumsy contemporary tools, adaptable only to articles of simple and fairly substantial form. The second was cast iron—hard, brittle, and weak because of its high carbon, but castable into fairly complicated shapes from small to really formidable sizes. The utility of a metal in which the desirable properties of both wrought iron and cast iron might be combined was plain to see. Many experiments were undertaken to develop such a metal. Some of them sound rather mysterious in the record—for example, the English patent issued June 21, 1630,[1*] to David Ramsey for a way "to make hard iron soft." There is no record of commercial application of Ramsey's process. Nor is there indication that ironmasters of the Seventeenth Century were interested in English patents Nos. 161, 164, and 165, issued in 1670[1] to Prince Rupert von der Pfalz, then living in England, even though the Prince claimed "a new invention or art of prepareing and softening all cast or melted iron, so that it may be fyled and wrought as forged iron is."

The first real advance was made by the great French scientist and metallurgist, R. A. F. de Réaumur, who published in 1720, 1721, and 1722 the first technical discussions of malleable castings.[2] The process of malleablization which Réaumur described consisted of melting iron, pouring castings, packing them in pulverized iron ore, and heating them to bright redness for many days. The type of furnace which was available to him is shown in Fig. 2. Lengthy heat-treatment in this temperature range slowly removed the carbon present as iron carbide in the metal as cast. This decarburization was partial to complete, according to the thickness of the casting and the temperature and time of heating. The metal thus produced was almost free from carbon and for the first time provided ferrous castings possessing some toughness and ductility.

Fig. 2. **This print from the encyclopedia of Diderot and D'Alembert, 1762, shows a small furnace such as was available to Réaumur in his early experiments with white-heart malleable iron.**

At elevated temperatures, the chemical affinity of oxygen for carbon is stronger than its affinity for iron. As Réaumur's carbide gave up carbon the iron ore packed around the castings released oxygen to combine with the freed carbon to form gaseous carbon monoxide and dioxide, which escaped from the furnace. The packing performed three functions: First it supplied the oxygen for oxidizing the carbon; second, it supported the castings that otherwise would have softened and lost shape under the applied heat; third, it acted as a "buffer," shielding the castings from direct contact with the hot furnace atmosphere—a contact which in the long period of heating would have caused undue oxidation of iron as well as carbon, creating a heavy scale on the castings and perhaps even destroying thin sections.

This process, with only minor deviations, has been followed in Europe to the present day in those foundries still producing "whiteheart" malleable iron. To understand this descriptive term, one must remember that this iron is decarburized in the sense that most of the carbon freed from its carbide has been eliminated, though not all the carbide may have been broken up into iron and carbon. The constituents of the annealed metal, therefore, are mainly iron and iron carbide, although some of the freed carbon may also remain. Because of the presence of the iron carbide, the grains of the metal, when under tension, stretch to a limited extent or not at all, and then shear through and across their sections along minute and fairly flat planes which reflect light. These minute reflecting planes give a whitish or grayish color to the ruptured surface, and hence its description as "whiteheart."

Since decarburization was the basis of Réaumur's process, only small castings could at first be made malleable by it. Larger ones were liable to be hard and brittle in the center. Though present-day manufacture of whiteheart malleable has advanced beyond these limitations, decarburization continues basic to it. Some graphitization—the precipitation of carbon from iron carbide and its retention in the casting as nodules of free "temper" carbon—does take place in whiteheart malleable castings during the heat-treatment, but small castings, say up to a half-inch section, are almost entirely decarburized. Heavier sections consist of a white rim and a core in which some of the carbon remains in the combined form and which contains some nodular graphite. The properties of the rim differ greatly from those of the core, and so the

Fig. 3. **The manufacture of iron cannonballs in the late 18th century, as depicted in a colored engraving by Pyne. Réaumur's furnace was similar to the one shown, blown with air, supplied by hand bellows.**

size of casting which can be made successfully in whiteheart malleable is still limited.[8]

Whiteheart malleable never found much use in America, and only one or two foundries were still making it as late as the end of the nineteenth century. The principal importance of Réaumur's achievement, from the point of view of this book, is the fact that it set a mark for another creative mind to shoot at, a century later.

At Newark, New Jersey, in 1820, Seth Boyden, whom Thomas Edison called "one of America's greatest inventors," and who was the founder of two United States industries, had set up an iron foundry. Knowing of the whiteheart malleable iron of Europe, he foresaw in the rapidly developing industries of his own country a potential market for such a material. On the Fourth of July in 1826, he set out on a series of experiments to find out how to make malleable castings. From the start of his investigations until September 1, 1832, he kept a diary,[4] recording his experiments individually, detailing the materials he used, and commenting explicitly on the results he attained. Thus we know that he possessed specimens of malleable iron made in England, where Réaumur's whiteheart process was in regular use, and that he had some generalized ideas about the purpose and utility of annealing as the whiteheart process employed it. It is plain from the record that his aim in launching his series of experiments was to duplicate the whiteheart malleable iron of Europe.

Constantly, in referring to his early trials, Boyden derogatorily described the fractures of his specimens as "black" and "gray"; and of the eleventh experiment, he wrote, ". . . the iron was tough when broken but rather too dark in color." His iron, as cast, was largely composed of iron carbide—hard, brittle, and easily shattered. At a broken cross-section it showed a white, steely fracture, and hence came to be called "white iron."

Because of the chemical composition of the pig irons available to him, Boyden's white iron contained less sulphur than Réaumur's, more manganese, and much more silicon. Silicon aids the dissociation of iron carbide into iron and free carbon. When free carbon remains in the iron, this dissociation is known as "graphitization"; when carbon is freed and then eliminated as in Réaumur's process, the dissociation is "decarburization." Hence in Boyden's "malleable" iron, for a heat-treatment comparable to Réaumur's, relatively more carbon was precipitated than in Réaumur's and remained in the iron as nodules of free temper carbon—simply because Boyden's heat-treatment was not long enough in duration to oxidize away more than a small portion of the carbon.

As his heat-treating experiments proceeded and his malleable approached the strength and properties he was striving for, Boyden must have been continually puzzled at its persistent refusal to show his conception of proper whiteheart fracture. Without realizing it, he was witnessing and recording the results of an entirely new process[5]—graphitization of hard white iron to malleablize it, rather than decarburization. His iron had no relation to the whiteheart product he was trying to imitate, had much better properties, and was in fact a new creation among ferrous metals—"blackheart" malleable iron, which, when broken, shows a dark velvety surface, and which has often been termed American malleable iron in distinction from whiteheart malleable as made in Europe.

The reasons for the blackheart fracture of American malleable are that when broken in tension its ferrite grains stretch and elongate until they rupture, so that at the point of rupture the cross-section of the end of the broken piece is like a very closely packed bundle of short and very fine needles; between these needles are minute spaces across which the needles throw shadows upon their neighbors; the nodules of free temper carbon interspersed through the material are black and where exposed darken its color. Thus the general color of the fractured surface is dark, although the tips of the needles—where they sheared at the last instant of parting—are shiny.

Boyden evidently assumed that the heating periods applied to European irons were long enough, for he never significantly extended them in his own practice. Had he sufficiently lengthened his anneal—though it would have taken many weeks—he could have eliminated from his malleable most of its free carbon, thus duplicating the decarburization occurring in the lower-silicon irons of Europe. But before such a procedure was thought of or attempted, the better qualities of graphitized blackheart malleable with its free temper carbon began to demonstrate themselves, and the malleable industry native to our country struck out upon its own course of development.

The man who founded the malleable iron industry in the United States was himself as versatile as the metal. Boyden was born at Foxborough (now Foxboro), Massachusetts, November 17, 1788, into a family skilled in the use of metal and in the exercise of inventiveness.[6, 7, 8] Our Boyden's father was another Seth, who ran a small forge and machine shop in Foxborough and was the inventor of a leather-splitting machine. That Seth's father, Uriah, is said to have cast some of the first cannon ever made in America, and was operating a foundry in Foxborough during the youth of his grandson Seth, the future inventor and the future founder of at least two American industries.

Seth Boyden of malleable iron fame (see Fig. 4) had little schooling in the formal sense, but had an excellent opportunity for sound training in metals in the parental forge and machine shop and the grandparental foundry. He made good use of his opportunity; by the time he was 15

Fig. 4. This statue in Newark, New Jersey, honors Seth Boyden, who began there, in 1826, the experiments from which American malleable iron originated.

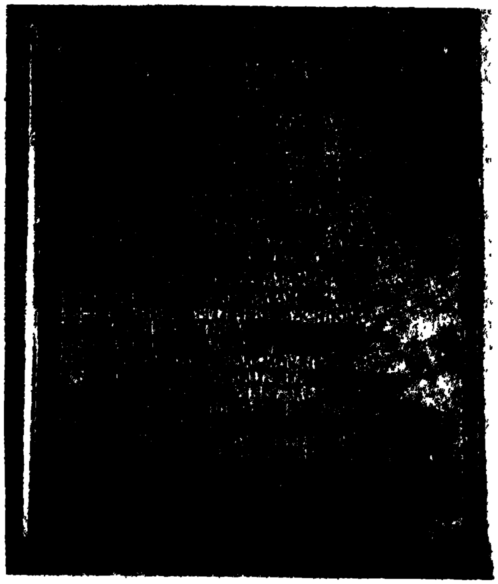
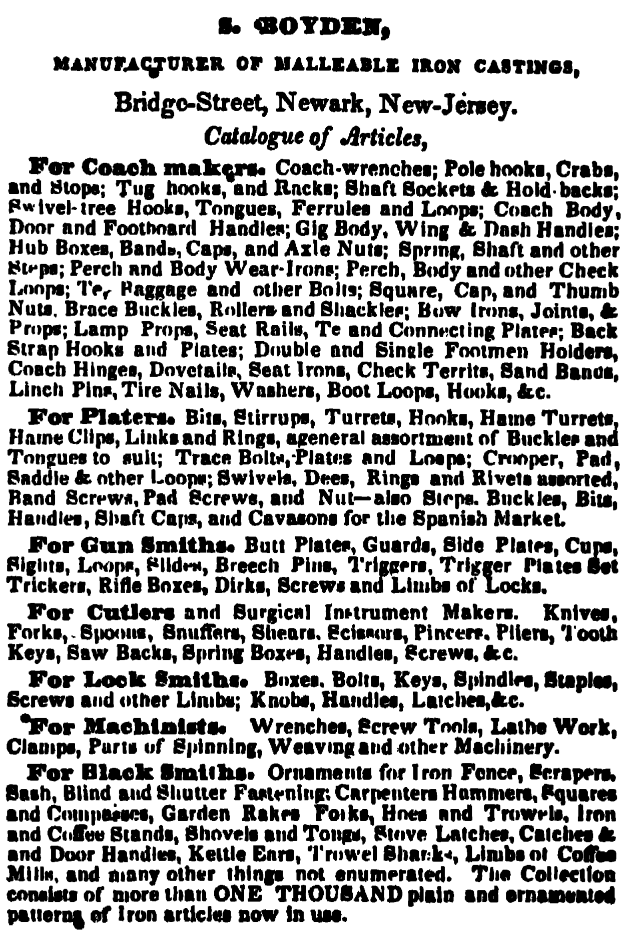


Fig. 5. This plaque on the base of his statue records some of Seth Boyden's achievements.

years old, he had built up considerable local renown for his skill in repairing clocks, watches, and guns, and for general ability as a mechanic. By the time he had reached his majority, he had constructed machines for making nails and cutting files. Four years later, in 1813, he went to Newark, New Jersey, with an improved leather-splitting machine of his own invention, to enter the business of supplying split sheepskins and leather to the bookbinding trade. In 1819, having succeeded in duplicating the lacquer of a piece of European ornamental leather, he opened the first factory in this country for the manufacture of varnished or "patent" leather, establishing the industry in America. He was 31 years old. His many achievements are commemorated on the plaque shown in Fig. 5.

Maybe he had gone far enough with leather to lose interest in it, or maybe simply because as a good Yankee he had to be starting a new enterprise, in the next year Boyden set up the Newark foundry. Here he was to be in business for the next 16 years, and here he was to do his research on malleable iron. He was a hard worker; only two years after he had started the experiments he won the silver medal offered by the Franklin Institute "for the best specimen of annealed cast iron; not *less than one dozen pieces, for various purposes, to be exhibited."* The committee of award declared Boyden's "assortment of buckles, bits, and other castings remarkable for their smoothness and malleability," and commented that "this is the first attempt in this country to anneal cast iron for general purposes, that has come under the knowledge of the committee, and the success attending it, fully entitles the maker to the silver medal."[6] In 1831, he was granted the first American patent for malleable iron.

Having thus once again done what he had set out to do, he sold his foundry business in 1837 in order to begin the manufacture of locomotives, and after he had built three of them turned to the making of stationary steam engines, in which he made the first application of "cut-off" governing.[7] Ten years later, in 1847, he adapted a grate bar for the manufacture of oxide of zinc—the grate bar which is still used today in the "American process" in the zinc industry. When the gold rush of 1849 had the East in a fever of excitement, Boyden, possibly deciding that he had earned a vacation, went West. The trip did not result in any gold mine for him, and in 1850 he returned to Newark. In the years remaining before his death on March 31, 1870, he developed a process for the inexpensive manufacture of "Russian" sheet iron, invented an important hat-forming machine, invented a goldlike alloy



S. BOYDEN,

MANUFACTURER OF MALLEABLE IRON CASTINGS,

Bridgo-Street, Newark, New-Jersey.

Catalogue of Articles,

For Coach makers. Coach-wrenches; Pole hooks, Crabs, and Stops; Tug hooks, and Racks; Shaft Sockets & Hold-backs; Swivel-tree Hooks, Tongues, Ferrules and Loops; Coach Body, Door and Footboard Handles; Gig Body, Wing & Dash Handles; Hub Boxes, Bands, Caps, and Axle Nuts; Spring, Shaft and other Steps; Perch and Body Wear-Irons; Perch, Body and other Check Loops; Ter Baggage and other Bolts; Square, Cap, and Thumb Nuts. Brace Buckles, Rollers and Shackles; Bow Irons, Joints, & Props; Lamp Props, Seat Rails, Te and Connecting Plates; Back Strap Hooks and Plates; Double and Single Footmen Holders, Coach Hinges, Dovetails, Seat Irons, Check Territs, Sand Bands, Linch Pins, Tire Nails, Washers, Boot Loops, Hooks, &c.

For Platers. Bits, Stirrups, Turrets, Hooks, Hame Turrets, Hame Clips, Links and Rings, ageneral assortment of Buckles and Tongues to suit; Trace Bolts, Plates and Loops; Crooper, Pad, Saddle & other Loops; Swivels, Dees, Rings and Rivets assorted, Band Screws, Pad Screws, and Nut—also Steps. Buckles, Bits, Handles, Shaft Caps, and Cavasons for the Spanish Market.

For Gun Smiths. Butt Plates, Guards, Side Plates, Cups, Sights, Loops, Slides, Breech Pins, Triggers, Trigger Plates Set Trickers, Rifle Boxes, Dirks, Screws and Limbs of Locks.

For Cutlers and Surgical Instrument Makers. Knives, Forks, Spoons, Snuffers, Shears. Scissors, Pincers. Pliers, Tooth Keys, Saw Backs, Spring Boxes, Handles, Screws, &c.

For Lock Smiths. Boxes. Bolts, Keys, Spindles, Staples, Screws and other Limbs; Knobs, Handles, Latches, &c.

For Machinists. Wrenches, Screw Tools, Lathe Work, Clamps, Parts of Spinning, Weaving and other Machinery.

For Black Smiths. Ornaments for Iron Fence, Scrapers. Sash, Blind and Shutter Fastening; Carpenters Hammers, Squares and Compasses, Garden Rakes Forks, Hoes and Trowels, Iron and Coffee Stands, Shovels and Tongs, Stove Latches, Catches & and Door Handles, Kettle Ears, Trowel Shanks, Limbs of Coffee Mills, and many other things not enumerated. The Collection consists of more than ONE THOUSAND plain and ornamented patterns of Iron articles now in use.

Fig. 6. **A typical page from Seth Boyden's catalogue, reputed to have been used as a calling card.**

known as "oroide," published a book on atmospheric electricity, contributed to the development of the famous Hilton strawberry, and all in all more than lived up to the traditions of Yankee ingenuity. He is reported to have made the first daguerreotype produced in America, and to have aided Samuel F. B. Morse, the inventor of the telegraph.

During his period as a founder, Seth Boyden made over a thousand different articles of malleable iron, as Fig. 6 suggests, including castings for coachmakers, for harness and saddlery, for gunsmiths, blacksmiths, and machinists. His first melting equipment was a crucible furnace, which was soon followed by an air furnace of a half-ton capacity, in which the charge was melted in a shallow hearth by flame drawn across it from fuel in the firebox at one end of the hearth to a stack at the other. Eight batches a day were sometimes taken from this furnace, which was not tapped, but was emptied by the molders, who dipped out molten iron in clay-washed ladles. About 1832, when he built the air furnace, Boyden employed 60 molders. His first annealing furnace was of beehive shape, with the pots inserted from the top. Next, to meet production schedules, he built a continuous annealing furnace with a sloping floor, which was known as the "shoving furnace" because pots were pushed in at the higher end and out at the lower.[9]

Boyden's original foundry at 25 Orange Street in Newark was operated under his own name until 1835, when it dropped out of business listings, and its former proprietor was classified as a "merchant" at 35 Bridge Street. It appears to have remained idle until 1838, when the firm of Condit and Bowles transferred to it as "Successors to S. Boyden" from their earlier establishment at 92 Orange Street. During this period, Seth Boyden was operating a steam engine factory on High Street. Three of his brothers—Otis, Alexander, and Frank—also became malleable iron foundrymen.[5] Otis was a foundry operator in Newark in 1835 and 1836, and in the latter year was one of the incorporators of the Newark Malleable Iron Manufacturing Company,[10] which, perhaps because of the panic of 1837, appears to have been a shortlived enterprise. Alexander and Frank were in business in East Boston, Massachusetts, until the former went to Easton, Massachusetts, to work for Frederick Fuller. Under the name of the Belcher Malleable Iron Company, the plant in Easton is still producing malleable iron castings. It is the oldest malleable iron foundry in continuous operation at the same site in the United States.[11]

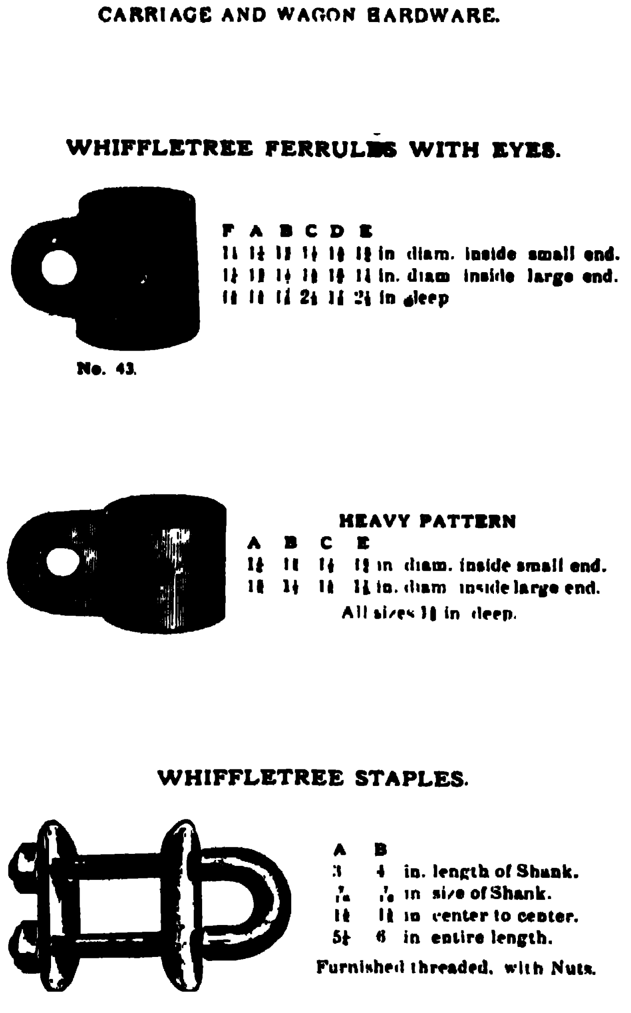
Within a decade or two after Boyden's establishment of malleable iron manufacture, the industry had spread from New Jersey through New England and New York, and in the 1850's it was expanding into Ohio and Illinois. The westward expansion of the country, with widespread building of railroads and a tremendous increase in the manufacture of agricultural implements, meant a growing demand for malleable iron. Before he died in 1870, Seth Boyden saw the industry spread as indicated by the following list of foundries which began making malleable iron during his lifetime and are still producing it:

Company	*Began Production of Malleable Iron*	*Original Name*
Westmoreland Malleable Iron Company Westmoreland, New York	1833	Oak Hill Malleable Iron Company
Belcher Malleable Iron Company Easton, Massachusetts	1837	Easton Iron Foundry
Meeker Foundry Company Newark, New Jersey	1843	Obadiah Meeker's Foundry
Frazer & Jones Company, Division Eastern Malleable Iron Company Syracuse, New York	1845	Frazer, Burns, and Jones
Arcade Malleable Iron Company Worcester, Massachusetts	1850	Arcade Malleable Iron Company
Malleable Iron Fittings Company Branford, Connecticut	1854	Totoket Company
Eastern Malleable Iron Company Naugatuck, Connecticut	1854	American Malleable Iron Company
Stanley G. Flagg and Company, Inc. Stowe, Pennsylvania	1857	Stanley G. Flagg and Company
The Dayton Malleable Iron Company Dayton, Ohio	1866	The Dayton Malleable Iron Company
National Malleable and Steel Castings Company, Cleveland, Ohio	1868	Cleveland Malleable Iron Company

In the early days of the industry, knowledge about both the melting and the annealing operation was scanty, and considerable mystery surrounded the craft. Each workman carried his secrets with him and zealously guarded any improvements in the process, lest a competitor discover them. The iron then was melted either in a crucible furnace or in a type of cupola, and charcoal pig iron was generally used. Air furnaces gradually supplanted the cupola because they permitted easier control of the composition. Since they had greater production capacity and cost less to run, they also displaced crucible furnaces. Early air furnaces were of 800 to 1,000 pounds capacity, and when one daring foundryman put in a charge of 1,500 pounds, the others viewed it with alarm as being too large to handle. In some of the earlier foundries, the furnace was built in a pit. When the heat was ready, instead of tapping and letting the metal flow out as is done today, a man stood beside the furnace with his arm protected by an old bootleg and lifted up the bung so that the molders could dip their ladles in the furnace to take out the iron.

As little was known in those days about temperature control, the heat-treatment or anneal was a process of guesswork, with good results hoped for but not necessarily assured. Annealing cycles varied from six to ten days. The annealing temperature was judged by eye, and references to its being insufficient and necessitating another anneal occur in the notebooks of the early founders. From the decarburized condition of some of the castings made about the middle of the nineteenth century, it is evident that during the anneal they were surrounded by a highly oxidizing packing such as mill scale or iron ore.

The first application of malleable iron was in saddlery hardware such as buckles, bits, snaps, and stirrups. Next came the use of malleable iron for carriage and wagon parts—hubs, hub bands, flanges, and steps, for example. (Fig. 7.) The use of this metal made possible greater production of vehicles; malleable iron castings were more nearly uniform in size than the handmade product of the blacksmith, and could be produced in quantity. The third large use for malleable castings in the early days of the industry was in agricultural implements. Small farm tools such as hoes and rakes of malleable iron had met with great success, as the toughness and shock resistance of the metal gave good service at



CARRIAGE AND WAGON HARDWARE.

WHIFFLETREE FERRULES WITH EYES.

F	A	B	C	D	E	
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	in diam. inside small end.
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	in. diam inside large end.
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	in deep

No. 43.

HEAVY PATTERN

A	B	C	E	
[illegible]	[illegible]	[illegible]	[illegible]	in diam. inside small end.
[illegible]	[illegible]	[illegible]	[illegible]	in. diam inside large end.

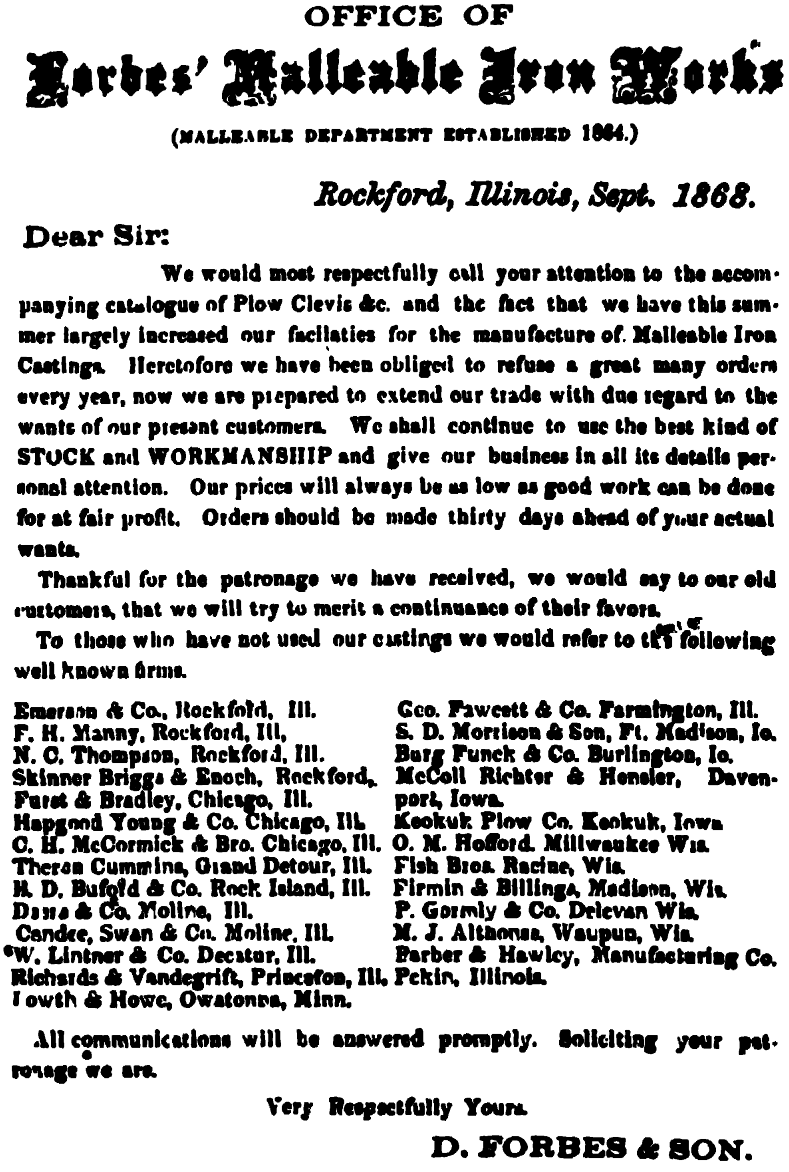
All sizes [illegible] in deep.

WHIFFLETREE STAPLES.

A	B	
3	4	in. length of Shank.
[illegible]	[illegible]	in size of Shank.
[illegible]	[illegible]	in center to center.
[illegible]	6	in entire length.

Furnished threaded, with Nuts.

***Fig. 7.* Page from one of the earliest catalogues of malleable iron showing carriage and wagon hardware. Castings like these were made in Seth Boyden's foundry in Newark in the 1830's.**



OFFICE OF

Forbes' Malleable Iron Works

(MALLEABLE DEPARTMENT ESTABLISHED 1864.)

Rockford, Illinois, Sept. 1868.

Dear Sir:

We would most respectfully call your attention to the accompanying catalogue of Plow Clevis &c. and the fact that we have this summer largely increased our facilaties for the manufacture of. Malleable Iron Castings. Heretofore we have been obliged to refuse a great many orders every year, now we are prepared to extend our trade with due regard to the wants of our present customers. We shall continue to use the best kind of STOCK and WORKMANSHIP and give our business in all its details personal attention. Our prices will always be as low as good work can be done for at fair profit. Orders should be made thirty days ahead of your actual wants.

Thankful for the patronage we have received, we would say to our old customers, that we will try to merit a continuance of their favors.

To those who have not used our castings we would refer to the following well known firms.

Emerson & Co., Rockford, Ill.
F. H. Manny, Rockford, Ill,
N. C. Thompson, Rockford, Ill.
Skinner Briggs & Enoch, Rockford,
Furst & Bradley, Chicago, Ill.
Hapgood Young & Co. Chicago, Ill.
C. H. McCormick & Bro. Chicago, Ill.
Theron Cummins, Grand Detour, Ill.
H. D. Buford & Co. Rock Island, Ill.
Dana & Co. Moline, Ill.
Candee, Swan & Co. Moline, Ill.
W. Lintner & Co. Decatur, Ill.
Richards & Vandegrift, Princeton, Ill.
Towth & Howe, Owatonna, Minn.
Geo. Fawcett & Co. Farmington, Ill.
S. D. Morrison & Son, Ft. Madison, Io.
Burg Funck & Co. Burlington, Io.
McColl Richter & Hensler, Davenport, Iowa.
Keokuk Plow Co. Keokuk, Iowa
O. M. Hofford. Millwaukee Wis.
Fish Bros. Racine, Wis.
Firmin & Billings, Madison, Wis.
P. Gormly & Co. Delevan Wis.
M. J. Althouse, Waupun, Wis.
Barber & Hawley, Manufacturing Co. Pekin, Illinois.

All communications will be answered promptly. Soliciting your patronage we are.

Very Respectfully Yours.

D. FORBES & SON.

Fig. 8. A page from the 1868 catalogue of a malleable iron foundry.

relatively low cost, and when the manufacture of farm equipment on an industrial scale began, malleable castings were selected for a large number of parts. As early as 1868, a catalogue of malleable iron castings for the agricultural implement trade listed a considerable number of satisfied customers, as Fig. 8 records. More than 90 years later the agricultural implement industry still relies on malleable iron for castings in making plows, reapers, mowers, binders, cultivators, and spreaders.[12]

Roughly a half-century after Boyden's patent had been issued in 1831, the industry based on it entered upon a period of rapid expansion. Demand for malleable iron increased markedly, new foundries were opened, and manufacturing methods were improved. The increased demand emphasized the importance of malleable castings to transportation. Saddlery and wagon parts were now joined by sprockets, chains, and forks for the growing bicycle industry, for one thing. But a far greater share of the increased demand came from a new purchaser, the railroad industry. By 1890, the railroads were taking a substantial part of the tonnage of malleable iron foundries for such castings as journal boxes and lids, wedges, drawbars, brackets, hooks, oil-box frames, brake equipment, door fasteners, stakepockets, turnbuckles, switch castings, and many others. As the railroads were the largest customer of the malleable iron industry during the period between 1890 and 1910, it is natural that the expansion of the industry took place along their routes. Many of the new plants were established through the Midwest. In general they were built in the area east of the Mississippi and north of the Ohio, roughly along the lines of the present Pennsylvania and New York Central railroads.[5]

By the turn of the century, when the automobile and allied industries were taking form, the foundry skill necessary to cast malleable iron into pieces of complicated design, and the manufacturing techniques required to take full advantage of its machinability had been secured. Experience in making conveyor chain, pipe and radiator fittings, railroad castings, parts for stoves, machinery, and bicycles, and wagon wheel hubs and flanges had prepared the industry for a new opportunity. The manufacturers of the first automobiles were naturally interested in a material which could be cast to shape in a wide range of sections and sizes, could be machined at relatively low cost, and was strong and tough enough to meet the severest operating conditions. The wagon builders of the previous decades had found malleable castings eminently suited to their requirements, and the wide use of it in automobiles was a natural consequence. The adaptation of the malleable iron automobile hub from the malleable wheel hubs and flanges used in wagons and buggies illustrates the borrowing of design and material. By 1910 the automotive industries had become heavy consumers of malleable castings, and they continue so today. It was not only in the manufacture of agricultural machinery and the development of land transportation that the useful properties of malleable iron were recognized; the swiftly growing industries based on electrical communications and the generation and transmission of electric power adopted malleable iron extensively in pole line hardware and many other applications.

As the malleable iron industry grew in response to these demands, steady improvement in methods of manufacture took place. Furnaces grew from the one- to five-ton capacity in the 1880's to as high as 40 tons by 1900. Still larger ones came into use by 1925.[13] Sand-handling machinery, molding machines,[14] and blast cleaning equipment mechanized, simplified, and speeded up the founding process and contributed to assuring uniformity in castings. The introduction of pulverized coal in air-furnace melting, at about the time of the first World War, and the subsequent development of improved pulverizing and separating equipment brought about a marked increase of efficiency in melting. Duplexing, the process of melting the stock in a cupola and then running the cupola melt into another furnace for refining, was first experimented with about 1912, was rid of its growing pains in a decade, saw its first permanent application in 1928, and three years later was being used to supply continuous metal. These developments were immediate results of the increased demand for malleable castings; they reflect also the influence of experimentation and research.

During most of its first half-century, the manufacture of American malleable iron, like much of the industrial activity of the nation during this period, had been mainly empirical in its approach. The age of industrial research as we know it had not begun. But by the 1870's inquiry into the reasons behind the practical success of particular methods in various industrial operations began to come into prominence, and in the following decades, both through the work of independent investigators and through the co-operative efforts of the industry as a whole, basic knowledge of process and product was gathered, to be shared through general publication. As a consequence, the malleable iron industry of the United States today promotes procedures for standardization of product and control of quality which assure the dependability of castings, and sponsors continuous research looking toward product improvement.

Probably the first scientific investigator of American malleable iron was Alfred E. Hammer of the Malleable Iron Fittings Company at Branford, Connecticut.[5] He had begun to study the chemistry of the process in 1872, and three years thereafter he established at the Branford plant the first chemical laboratory in the industry. Studying the effect of different proportions of carbon and silicon and of manganese and sulfur, he worked out chemical ratios for each pair, and subsequently applied these in the selection and mixing of irons where they were the more valuable in view of the fact that at the time pig iron was not made and sold by analysis. B. J. Walker of the Erie Malleable Iron Company actively fostered studies similar to those in which Mr. Hammer engaged, as did A. A. Pope of the Cleveland Malleable Iron Company, now the National Malleable and Steel Castings Company of Cleveland, Ohio. Publication of the kind customary today was by no means frequent in the years around the Centennial Exposition, so that it was entirely natural for an investigator to hold confidential the useful results which he attained. Mr. Hammer and Mr. Walker nevertheless began, in the 1880's, to share their knowledge of malleable iron and the science underlying it.

More of the larger malleable iron manufacturers established laboratories after 1890. One of these was the Walter A. Wood Mowing and Reaping Machine Company of Hoosick Falls, New York, which opened a well-equipped laboratory in 1894. At that time the Wood firm engaged as consultant Enrique Touceda, who had come from Cuba to study the arts at Georgetown University and the sciences at Rensselaer Polytechnic

Institute. At Rensselaer, he worked with Professor Palmer C. Ricketts in studies of malleable iron which led to some of the earliest publications on the subject. Dr. Touceda was later to play a dominant role in the development and improvement of malleable iron techniques on an industry-wide basis. In 1904, the National Malleable and Steel Castings Company set up a works and experimental laboratory at Indianapolis. Here Dr. Harry A. Schwartz, using as a nucleus the information which Mr. Pope had assembled, commenced investigations looking toward the establishment of a sound theoretical basis for process control. The quantitative effect of carbon on the melt was determined in the first year of this research, and subsequently the lack of effect of manganese sulphide was established. The theoretical explanation thus derived for the practical observations which Messrs. Hammer, Pope, and Walker had made 20 years before was similarly arrived at by other investigators, prominent among whom was W. R. Bean, then of the T. H. Symington Company of Corning, New York, later of the Eastern Malleable Iron Company, Naugatuck, Connecticut. Further studies of the effect of the carbon content on the strength of castings, and of the carbon-silicon, sulfur-manganese, and silicon-phosphorus relations were carried on in the period after 1903 by Dr. Schwartz, Mr. Bean, and Allen Bixby of the Indianapolis Works of the National Malleable and Steel Castings Company.

Except for the early publications by Professor Palmer C. Ricketts and Enrique Touceda which have been mentioned, general publication remained a rare thing until Dr. Richard Moldenke, after having been associated with the laboratories of two malleable iron concerns, established himself as an independent consultant and commenced frequent contributions to technical journals. For a considerable number of years, his were almost the only published treatments of malleable iron and its chemistry, and he was a stout advocate of greater exchange of ideas. Through work of this sort and through subsequent research which turned from the chemistry to the physics, metallurgy and metallography of malleable iron, further progress was made toward assured control of the product. Among the subjects discussed were the structure of malleable iron, the question of high iron oxide in sands as a possible source of surface trouble in castings, the problem of gas entrapment, the use of powdered coal as a fuel, and the elimination of galvanizing embrittlement. Prominent in these investigations were Dr. Schwartz and Mr. Bean, and two of his associates at Eastern Malleable Iron Company, H. W. Highriter and E. K. Smith. As a practical means of studying the toughness of malleable iron, the wedge test was developed during this period by B. J. Walker of the Erie Malleable Iron Company. It is regarded as particularly valuable from the performance point of view, because it tests the shock resistance of an unmachined specimen.

Oliver Storey of the Wisconsin Malleable Iron Company, in studies of the graphitizing reaction, was among the first to show in published writings about 1912 and 1913 a thorough understanding of this reaction as related to the iron-carbon diagram. Slightly later was pioneer work by Paul Merica of the National Bureau of Standards in the theoretical metallurgy of malleable iron. The University of Michigan sponsored work on the measurement of the effect of graphitizing rates, about 1917, the investigations being under the charge of A. B. White. Professor Anson Hayes and his graduate students at Iowa State University somewhat later published a considerable amount of information dealing with the effects of various alloy elements.

The investigations and advances summarized thus far all had to do with standard malleable iron—metal consisting of a ferritic matrix through which are distributed nodules of free carbon which had been made in the United States since Boyden's day. Pearlitic malleable iron—in which some of the carbon content is in the combined form as iron carbide—was first made a matter of record in June 1919, when Professor Touceda described a pearlitic malleable structure in a paper read before the American Society of Mechanical Engineers. Professor Touceda showed a photomicrograph of the material, "a ground-mass of pearlite in which are more or less uniformly distributed nodules of temper carbon," and expressed the opinion that this high-strength metal—his specimen had a tensile strength of 84,000 pounds per square inch and an elongation of 5.2 per cent—could be produced with a 10 per cent elongation.

In the years immediately following this first disclosure, investigation and invention in the pearlitic malleable field went on apace. Professor J. W. Diedrichs of Cornell University obtained a patent on a type of pearlitic malleable iron in December, 1919. Studies carried on at the Naugatuck, Connecticut, plant of the Eastern Malleable Iron Company and at the Lakeside Malleable Castings Company, Racine, Wisconsin, were discussed by E. K. Smith in a paper on pearlitic malleable iron presented at the 1923 Convention of the American Foundrymen's Association. Mr. Smith and W. V. Osborne, in the preceding year at the Racine plant, had produced and sold hammers and hatchets made of pearlitic malleable iron. Early records recount the production of detachable chain in pearlitic malleable iron at the Indianapolis plant of Link-Belt Company in August, 1925. In October of that year, a patent application was made by Stanley W. Ewing of National Malleable and Steel Castings Company, covering a type of pearlitic malleable. Professor Diedrichs and Professor Hayes of Iowa State University took out additional patents in 1926, and various patents on pearlitic malleable were issued to C. F. Lauenstein and associates of Link-Belt Company in the years 1927-30. Most of the pearlitic malleable iron patents have now expired, although copyright trade names are still protected.

This discussion of research and improvement thus far has been in terms of individual contributors, in order that the story of how the industry has co-operated as a whole might be told coherently.

One of the first co-operative industrial groups in the United States was formed by the malleable iron industry, when a group of manufacturers met in New York in 1897 under the chairmanship of O. P. Letchworth of Pratt and Letchworth, to found the American Malleable Castings Association. This was an association whose members agreed to share knowledge of practice and thus improve the product of all. E. C. Metcalf of the Westmoreland Malleable Iron Company, Westmoreland, New York; Fred Frazer of the Frazer and Jones Company, Syracuse, New York; Harry Forbes of the Rockford Malleable Iron Works, Rockford, Illinois; B. J. Walker of the Erie Malleable Iron Company, Erie, Pennsylvania; Amos Whitely of the Muncie Malleable Foundry Company, Muncie, Indiana; Frederick W. Sivyer of the Northwestern Malleable Iron Company, Milwaukee, Wisconsin; W. H. Osborne of the Wisconsin Malleable Iron Company, also of Milwaukee; and John T. Llewellyn of Belle City Malleable Iron Company, Racine, Wisconsin, were among the group concerned with the formation of the association.

Other leading malleable foundrymen who made their influence felt in co-operative activies during the period from 1900 to 1920 were John C. Haswell of the Dayton Malleable Iron Company, Dayton, Ohio; Frank J. Lanahan of the Fort Pitt Malleable Iron Company, Pittsburgh, Pennsylvania; J. H. Whittemore and Bronson B. Tuttle, under whose guidance several malleable foundries were developed which finally merged in 1912 into the Eastern Malleable Iron Company with headquarters at Naugatuck, Connecticut; and A. A. Pope, who with Mr. Whittemore, Mr. Tuttle and Howard Coonley founded and developed the group of plants constituting the National Malleable and Steel Castings Company, Cleveland, Ohio.

After experience had demonstrated to the American Malleable Castings Association the diversity of opinion existing among even the best informed about the manufacture and properties of malleable iron, a program of intensive research was decided upon. For that purpose the association, in 1913, retained Enrique Touceda who, as we have seen, had become associated with malleable iron through the Walter A. Wood Company nearly 20 years before. Professor Touceda, shown in Fig. 9, who was recognized as a consulting metallurgist of great skill, was commissioned to carry out what is considered[15] the first co-operative research program entered upon by an industrial group in the country. He undertook to conduct a series of fundamental research projects and to report to the Association the information thus gained. The group agreed to forego the long established custom of individual safeguarding of trade secrets, and to turn over to Professor Touceda all the knowledge then available to the industry. The investigation was three-pronged, calling for chemical, metallographic, and mechanical tests and examinations. Daily

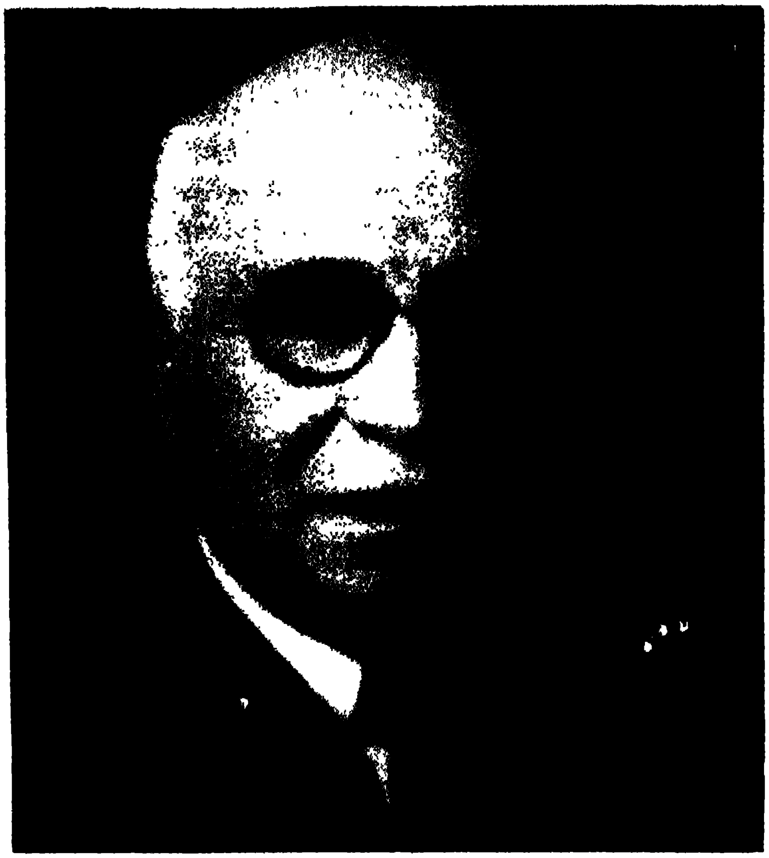


Fig. 9. **Enrique A. Touceda, for half a century foremost contributor to the development of malleable iron.**

test bars were supplied to the Association laboratory by members for use in the testing program, which aimed to maintain high standards of production and performance. Trained technical men from the laboratory, making periodic visits to each company to inspect practices in the foundry, aided the adoption of approved methods.

The American Malleable Castings Association was succeeded in 1927 by the Malleable Iron Research Institute, which placed special emphasis on improvement in the properties of malleable iron and in the processes of manufacture. The activities of the Institute were turned over in 1934 to the Malleable Founders' Society, which is thus the inheritor and the embodiment of a sixty years' tradition of co-operation in research and quality control, and which has greatly broadened the range of its service to the industry. The Society today retains an expert staff of engineers and metallurgists, continues its consolidated program of plant inspection and technical research, and maintains its own metallurgical testing laboratory where constant effort goes on for improvement of process and product and for the maintenance of the highest standards of performance and quality control. The Society awards annually the Charles H. McCrea medal (Fig. 10), established by the National Malleable and Steel Castings Company in honor of Mr. McCrea, its former president. The purpose of the award is to encourage and stimulate individual effort in the progress

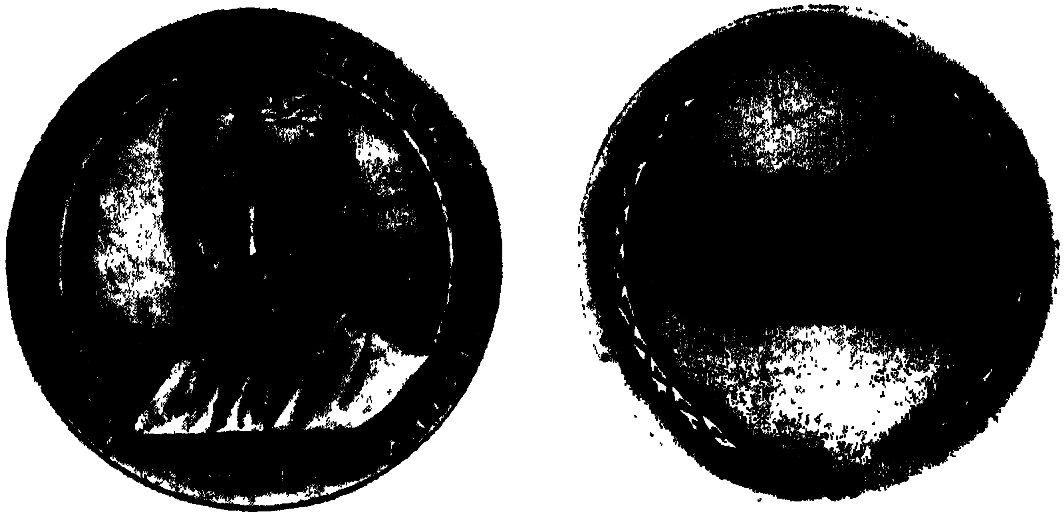


Fig. 10. The Charles H. McCrea medal.

and development of the arts and sciences practiced in the malleable iron industry. The Society, in addition, carries on a comprehensive trade association program which comprises product promotion, the collection and distribution of statistics, the conduct of educational meetings for technical and operating personnel to improve processes and products, representation of the industry before Government agencies, and other services designed to foster the general welfare of the industry. These range from special consultation with prospective new users of malleable castings to the preparation of colored motion pictures and publications such as this handbook to present the story of malleable iron to student groups, engineering societies, and others interested.

The best yardstick to measure the achievements attained through the research of individuals and of co-operating groups is the constant advance in the quality and uniformity of malleable iron. What was unusual in the pioneering days of the industry is now standard practice in control of the material from the charge through melting, casting, and heat-treatment. Specifications have steadily bettered as a consequence. A look at the record shows the first published test results on malleable iron in this country to have been those which Professor Ricketts[10] published in 1885. Average values for one set of 12 square test bars were about 38,000 pounds per square inch tensile strength and elongation of 3 per cent in five inches. Today's standard malleable iron offers users a typical tensile strength of 52,000 pounds per square inch and elongation of 12.5 per cent in two inches in one grade, and typical tensile values of 55,000 pounds per square inch and elongation of 20 per cent in two inches in another. In pearlitic malleable irons, the users may have minimum tensile strengths exceeding 100,000 pounds per square inch with elongations of 2 per cent minimum in two inches, and with marked increases in resistance to abrasive wear. This is what research, care, and control have accomplished.

Malleable iron castings can be bought today from any of more than a hundred foundries with full confidence in the specification quality of the metal. With an estimated annual capacity of 1,350,000 tons in plants distributed widely throughout the United States and Canada, the malleable iron industry is meeting a steadily growing demand. Malleable iron is finding a constantly increasing usefulness to every important industry. Its wide utility as an engineering material has been recognized abroad to such an extent that it has replaced a substantial amount of whiteheart malleable iron in whiteheart's European homeland.

Thus, over a century and a quarter after Seth Boyden started his experiments, the industry which he founded has become an integral and vital element in the industrial economy of the nation.

II

THE USES OF MALLEABLE IRON CASTINGS

Malleable iron castings are used in virtually every branch of American industry. Modern technology has made malleable a metal uniquely capable of meeting the most diverse design, production and performance requirements. Whether the vital consideration is high strength, toughness, ductility, hardness, machinability, appearance, high

***Fig. 1.* Small conveyor chain links, representing the smaller castings made in malleable iron.**

or low temperature performance, wear resistance, or economy and adaptability for complicated designs, malleable castings have the versatility to meet exacting specifications. To itemize one by one the thousands of commercial applications is outside the scope of this book. The list would be impressive, but it would run to unwieldy length, for it would include a multitude of components for every major division of the metalworking industry.

This chapter, therefore, will present a concise survey of typical present-day uses of malleable iron, which demonstrate the versatility and reliability of the metal. Representative castings illustrating its use in major industrial categories are shown in the figures; the text will discuss, in summary fashion, the examples which illustrate especially well one or another of the desirable qualities of ferritic and pearlitic malleable castings. From this capsule presentation of malleable's role in industry, the reader will derive background that will be useful as he reads later chapters discussing in detail its specific valuable characteristics and properties.

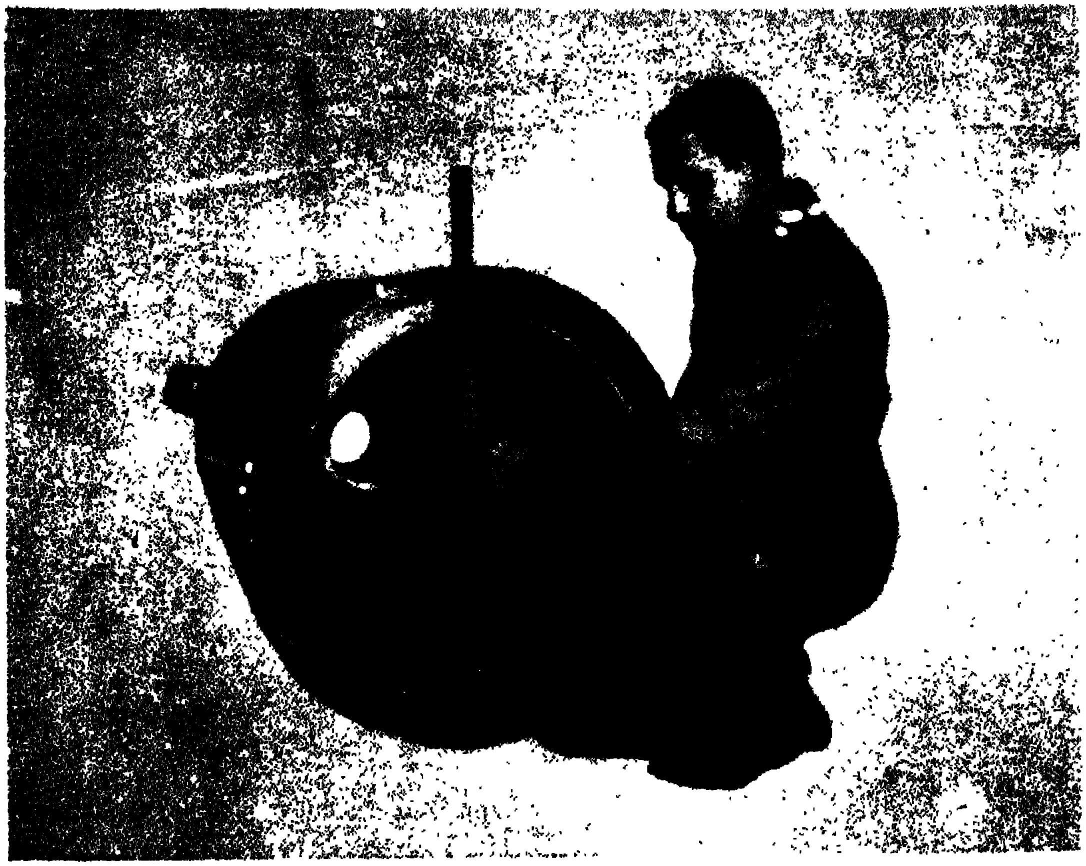


Fig. 2. **Weighing 3,960 pounds and measuring 36 inches in diameter by 38 inches high, this ingot mold shows the larger range of castings made in malleable iron. It is produced in standard malleable and has a section thickness exceeding 7 inches.**

The range of applications is a wide one. In size, it extends from small chain links, weighing a fraction of an ounce, to a giant ingot mold weighing 3,960 pounds. Some sections of this latter casting are more than 7 inches thick.

Fig. 3. Malleable iron is cast in a variety of shapes; these examples of a block, ring, nipple and washer illustrate some of the simple shapes produced.

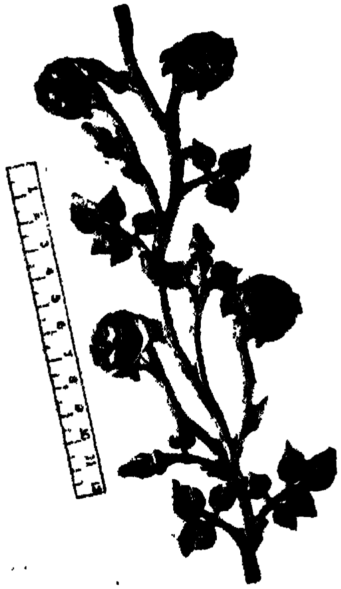
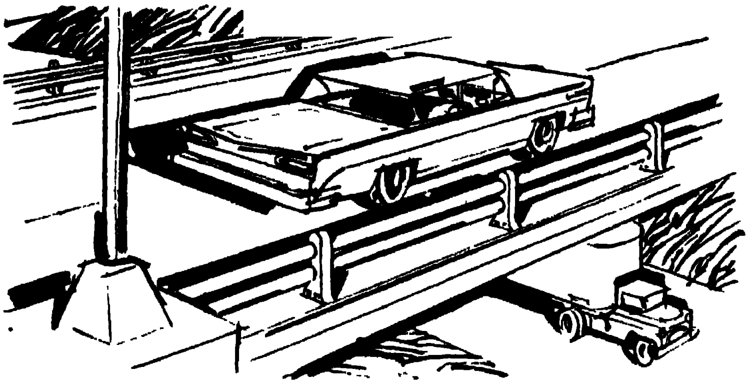


Fig. 4. This malleable casting is used in ornamental iron railings, and demonstrates the fine finish and detail obtainable.

Fig. 5. This pearlitic malleable gear case illustrates the ease with which complex configurations can be cast in malleable iron.

In design, it comprises both the simple shapes of rings, washers and blocks, and also complex structures with intricate configurations, such as gear cases. In utility, it extends from ornamental iron railing castings—where the fine finish and excellent detail demonstrate the castability of malleable iron—to automotive universal joint yokes and flanges, pearlitic malleable iron castings highly stressed in service. These yokes and flanges also exemplify the ready machinability and excellent surface finishes which may be achieved.



Malleable irons—both standard and pearlitic—are used in many vital applications in automotive vehicles. One familiar example is the truck rear axle banjo housing weighing 358 pounds. Strength and economy, important in all applications of metal, are especially valuable in the automotive field. They are also the reasons why malleable iron is specified for many parts in other heavy duty equipment, such as a tandem axle assembly.

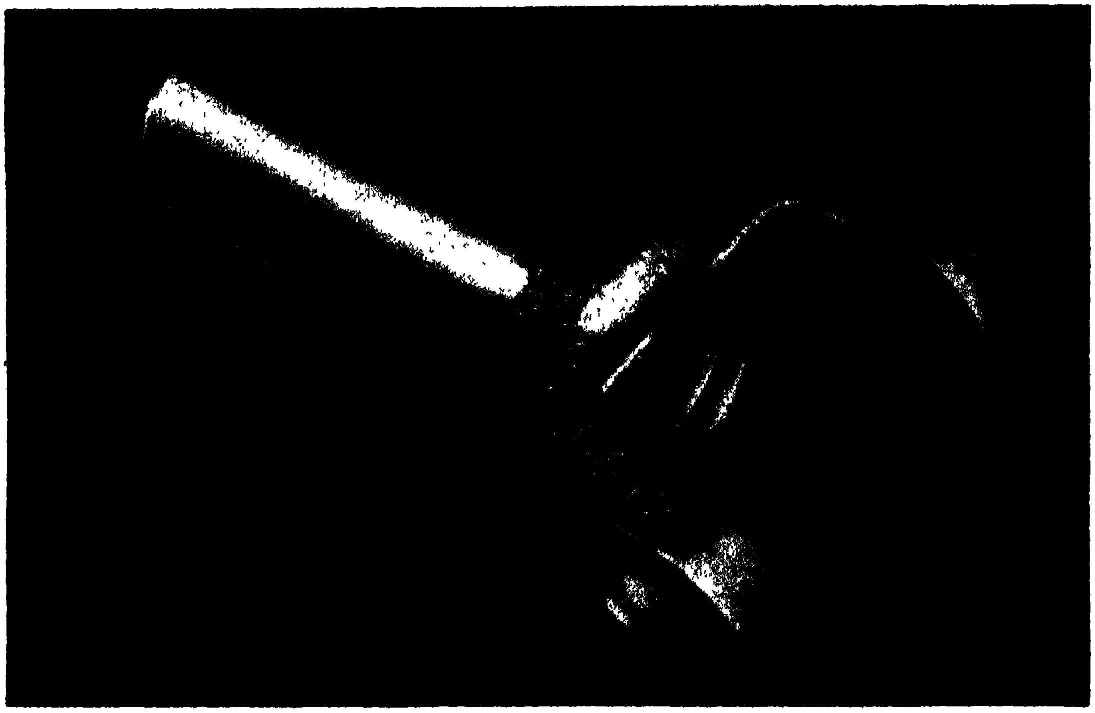


Fig. 6. **Millions of these universal joint yokes have been produced for passenger cars. Made in pearlitic malleable iron, these yokes are a vital link in the drive mechanism of automobiles.**

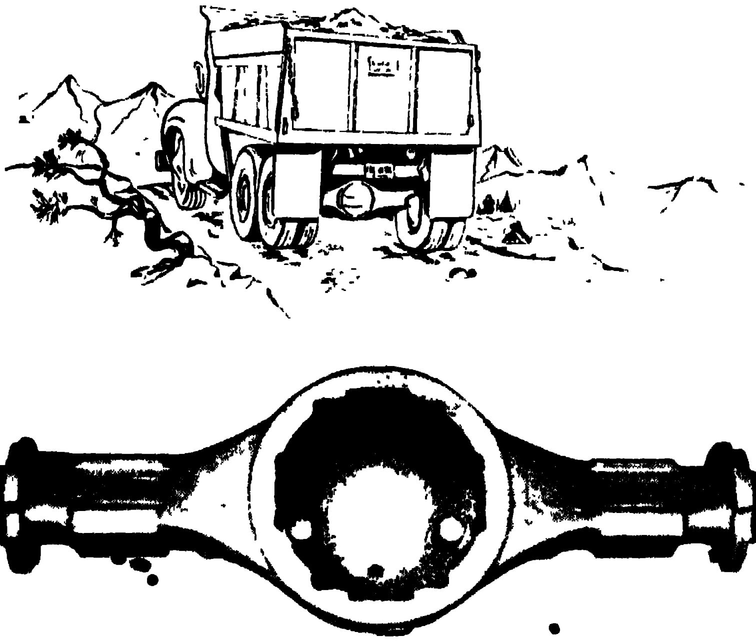


Fig. 7. The familiar rear axle banjo housing provides tough, rugged dependability for many of America's leading truck manufacturers. Illustrated is the actual banjo casting, and, in the drawing, its ultimate usage.

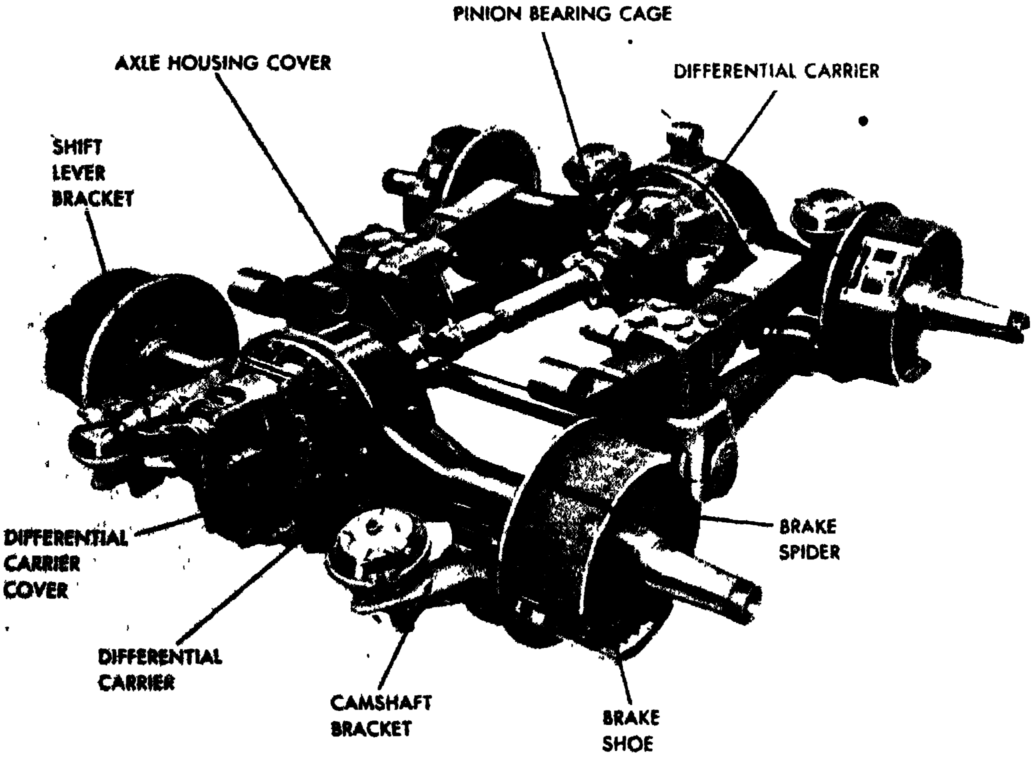


Fig. 8. Another heavy-duty application of malleable iron is the truck tandem axle assembly that utilizes malleable iron for such parts as pinion cages, differential carriers, shift lever brackets, differential covers, camshaft brackets and brake shoes.

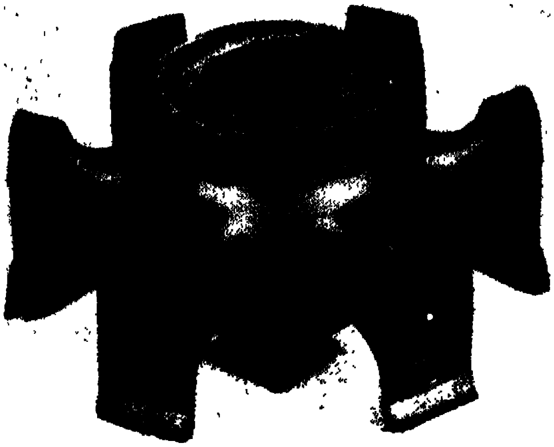


Fig. 9. This truck wheel spider is typical of a rugged application of malleable iron.

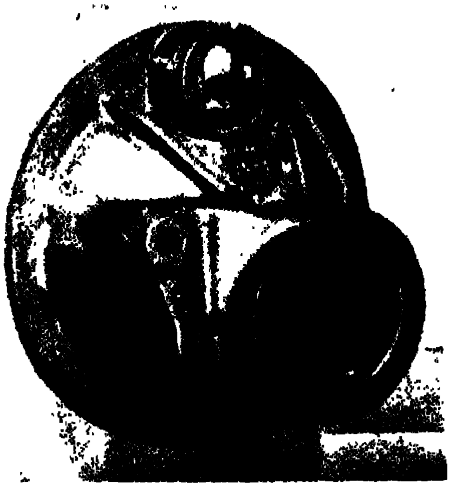


Fig. 10. This differential carrier combines the precision, economy and dependability of malleable iron castings.

Truck wheel spiders and axle differential carriers are further common examples of malleable's use in the automotive field. These parts must be very rugged to withstand heavy service, and their continued use through the years demonstrates their ability to perform well in these highly important components.

Pearlitic malleable iron automotive crankshafts must withstand repeated shock loading in use. Conversion to malleable resulted in an initial saving, and malleable's excellent machinability added further savings through a reduction in machining cost. Improved bearing life was a by-product of this conversion.

"Strength where you need it" is of vital importance in well designed parts. As an example, a pearlitic malleable rear spring clip pad was originally a stamping. In redesigning it as a casting, its weight was reduced from 4.2 to 2.9 pounds, and the yield strength of the part was increased.

Fig. 11. Automotive crankshaft weighing 85½ pounds and 25-7/10 inches in length. Pearlitic malleable provides economy in manufacture, good vibration damping characteristics, high strength and longer wear, which combine to give the automobile manufacturer an ideal material for this application.

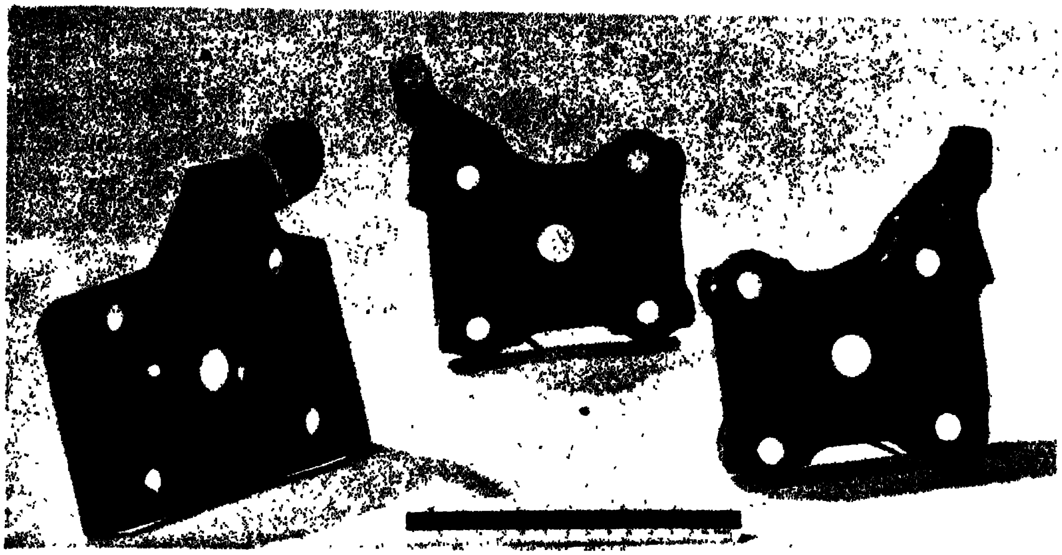


Fig. 12. This rear spring clip pad was originally a stamping, as shown at left. Stress analysis resulted in the functionally designed malleable casting shown in two views at center and right which has a higher yield strength, is more economical to make and weighs 1.3 pounds less.

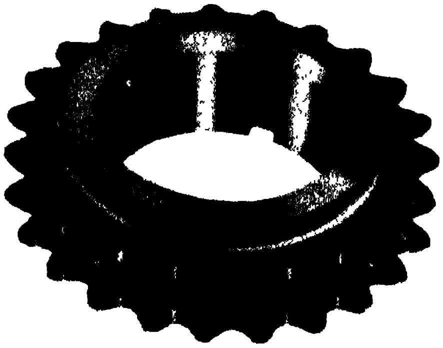


Fig. 13. Crankshaft sprocket. Machinability and susceptibility to selective hardening are the important reasons for specifying pearlitic malleable for this part.

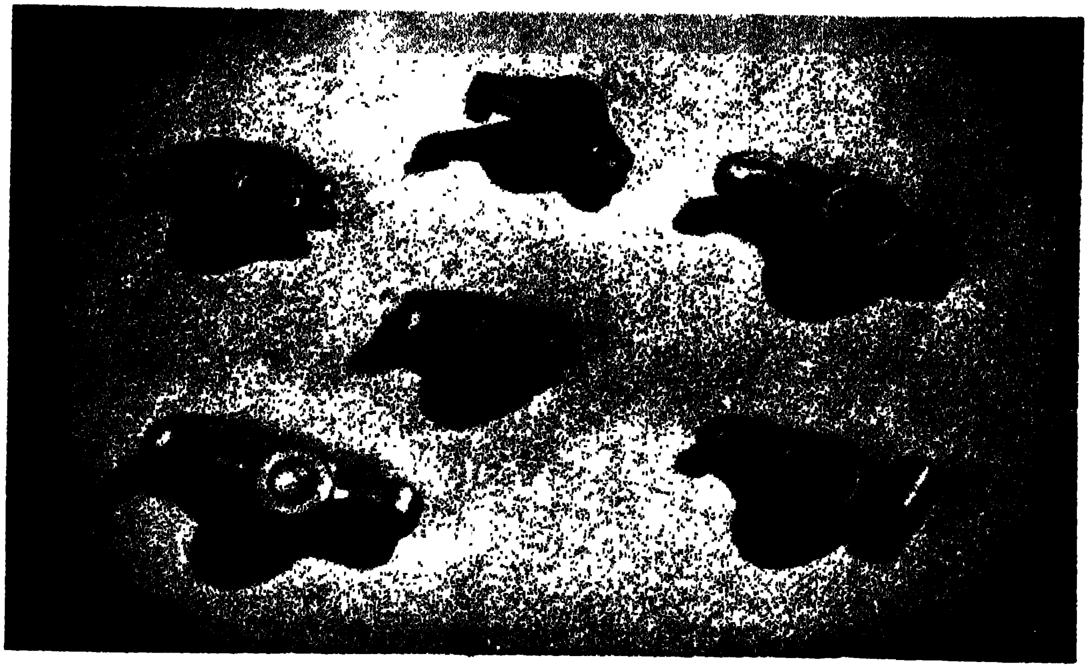
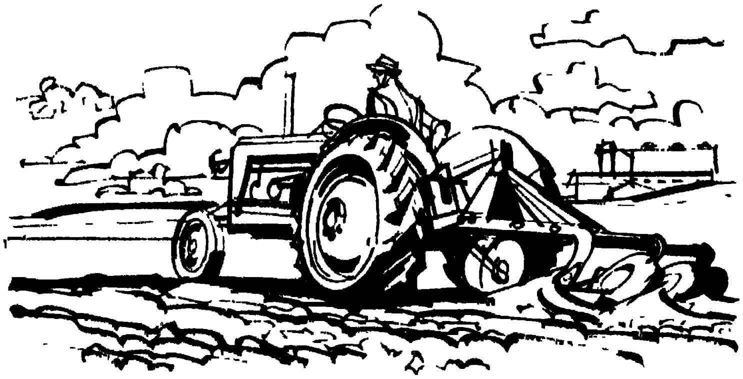


Fig. 14. Castability, strength, and ease of selective hardening have made pearlitic malleable iron the choice for rocker arms in internal combustion engines.

This is another example of the effective use of malleable's castability, strength and impact resistance.

Rocker arms for internal combustion engines have long been made in pearlitic malleable iron. Selective hardening characteristics make it ideal for applications requiring wear resistance, such as the push rod pad. Coining of the hubs to close tolerances eliminates machining at the hubs. Because of the excellent bearing properties of pearlitic malleable, bushings are usually dispensed with. In this same vein, the material's ready adaptability to selective hardening by flame or induction methods is important in crankshaft sprockets where the teeth must be hardened to a minimum of 55 Rockwell C.



The rugged strength, castability and machinability that make malleable iron a major material in automotive construction are comparably important in the manufacture of agricultural equipment. The hydraulic ram anchor for a disk harrow is subjected to heavy impact in use. In addition, the specification of malleable iron for this part yields good corrosion resistance. In converting from a weldment, a weight reduction of 30 per cent was achieved.

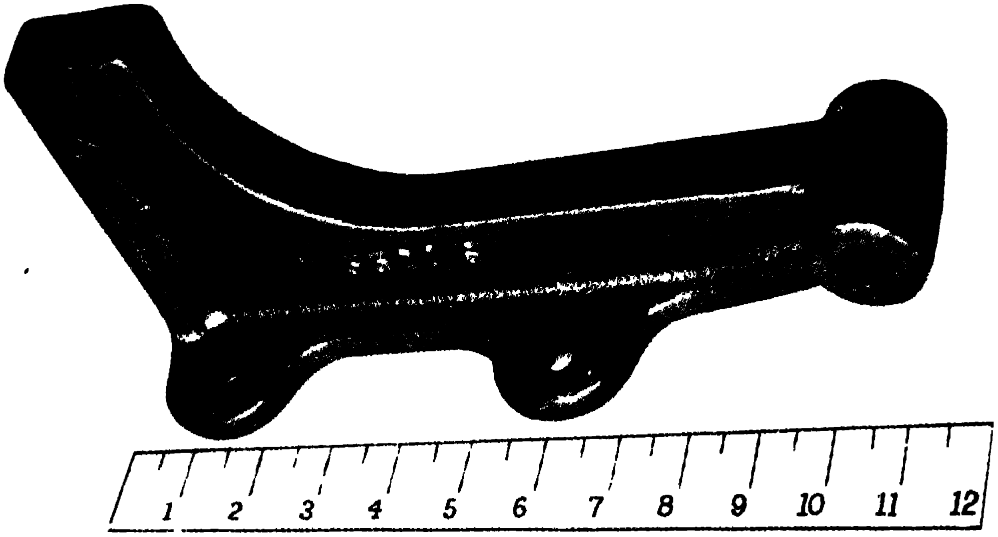
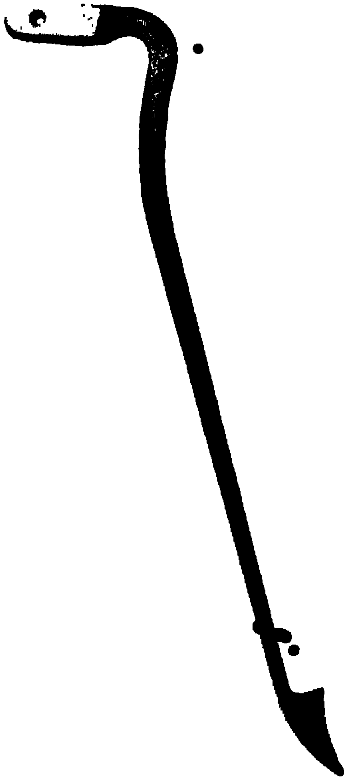


Fig. 15. The hydraulic ram anchor for a disk harrow was formerly a weldment. In converting to malleable iron, a weight reduction of 30 per cent was achieved, and improved corrosion resistance and strength characteristics provide a better part at lower cost.



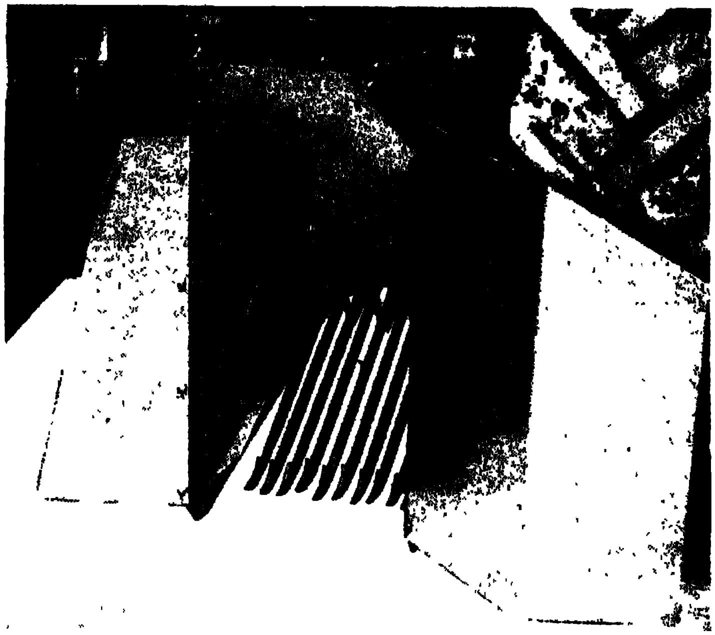


Fig. 16. Breakage was a common problem when these parts were made of another material. By using standard malleable iron for this 30-inch tooth for a cotton stripper machine, the manufacturer was able to eliminate this breakage problem. The cotton grower benefits in two ways: tough malleable teeth do not snap off, and an improved mounting method, made possible through the use of castings, permits adjustments in the spacing for different types of cotton.

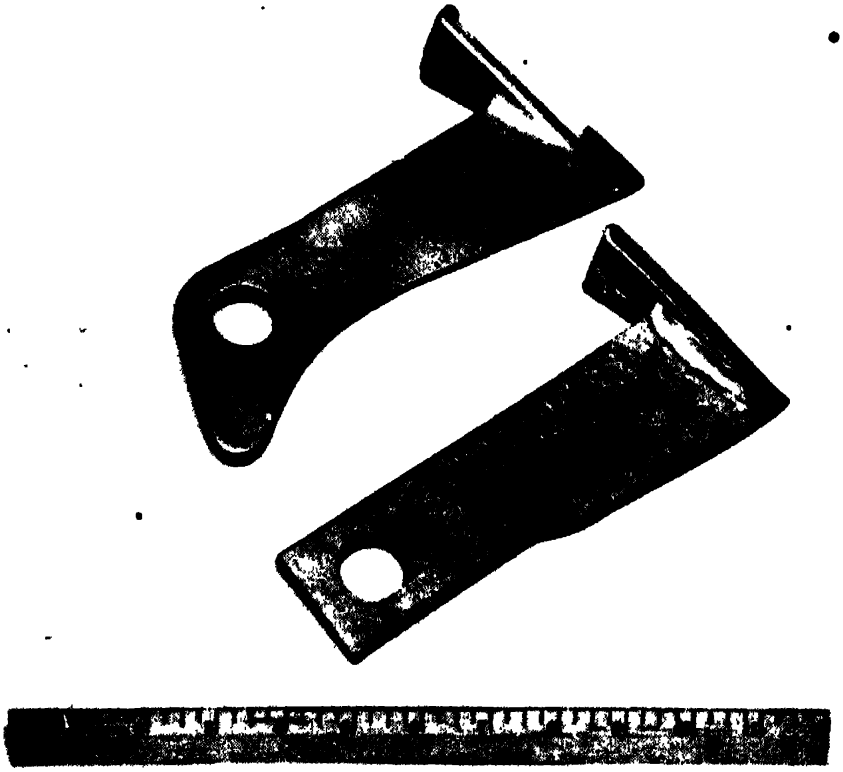
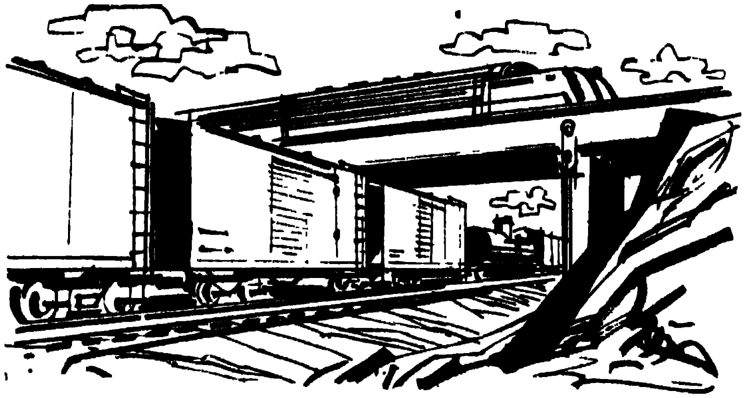


Fig. 17. This pearlitic malleable hay hammer (top), provided a part with greater strength as compared to weldment (below) and better corrosion resistance, as well as improved appearance through simplification of the design.

Long and thin, but tough and strong, thanks to the high strength of standard malleable, are the teeth used in a leading cotton stripper machine. These castings, 30 inches long, are less than 3/4 of an inch thick through most of their length. Breakage, even under the most severe operating conditions, was eliminated by specifying malleable.

Pearlitic malleable hay hammers further illustrate the utility of malleable in the conversion of weldments to castings. Not only was additional strength achieved, but the appearance was improved by simplified design.



Malleable iron components for railroad equipment, where dependability is so essential to the safety of the passengers and freight, have had their place in the railroad picture since the earliest days. Brake beam parts and axle roller bearing adapters are representative of such installations where strength and reliability are a prime requisite. Still another

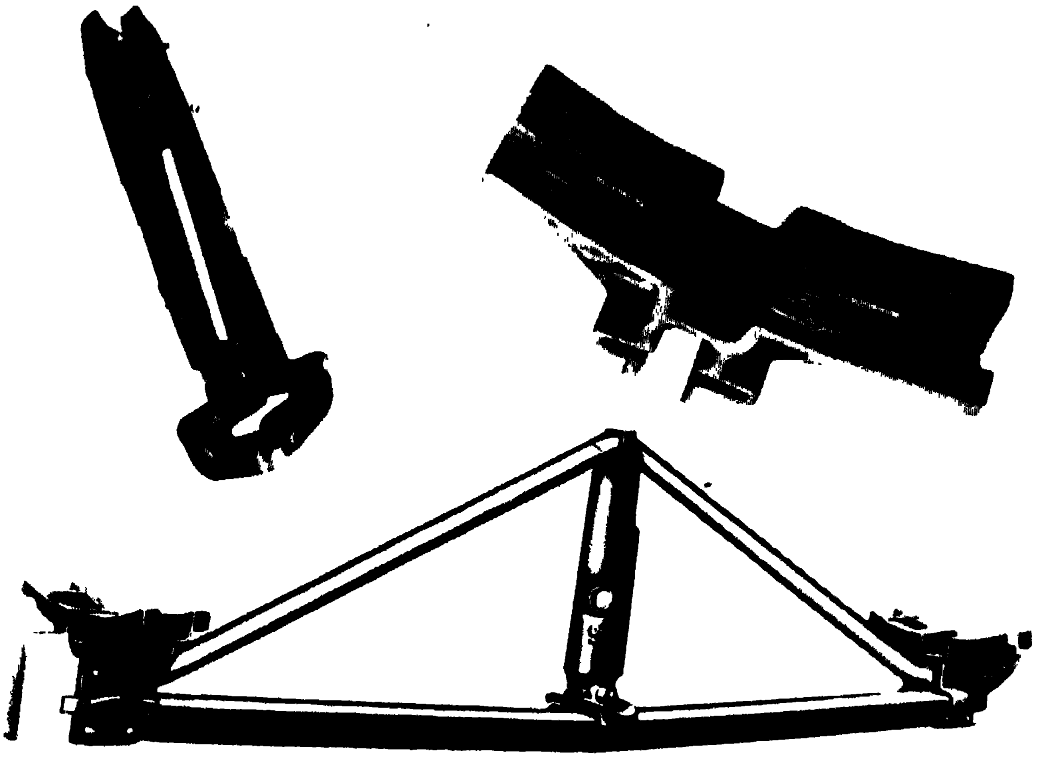


Fig. 18. **Malleable iron has long been used by railroad car manufacturers because of its economy, dependability and toughness. Brake beam parts shown in the figure are typical examples of the many parts specified in malleable.**

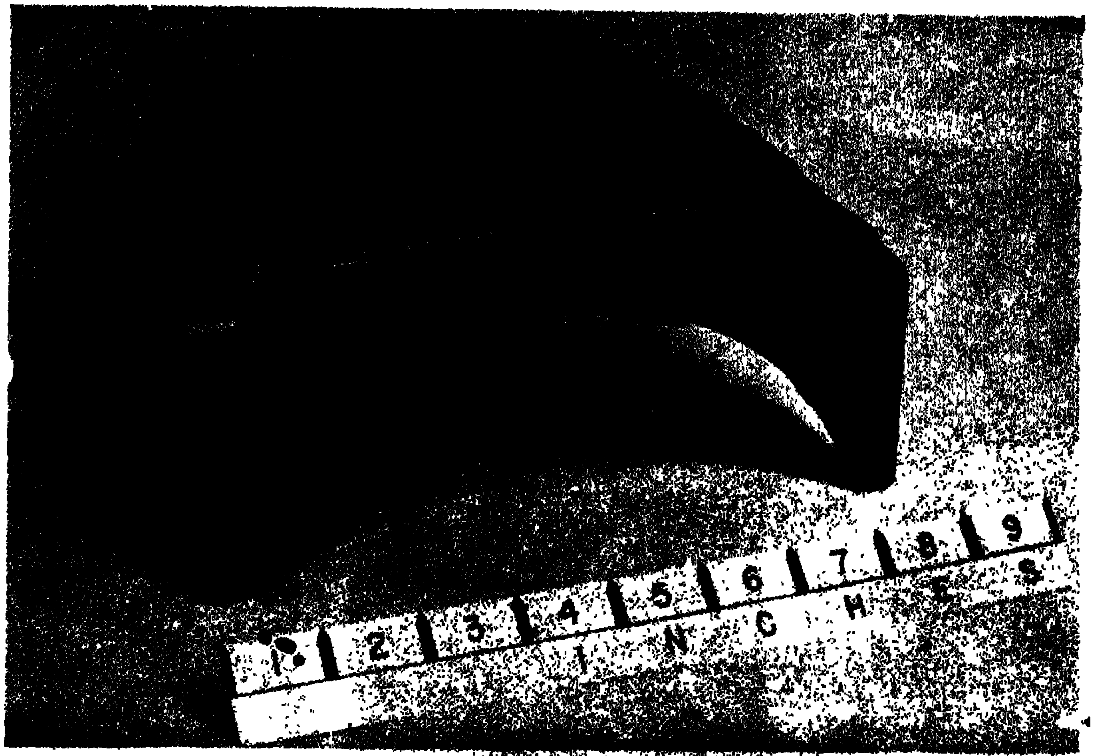


Fig. 19. Axle roller bearing adapters, such as this one made of pearlitic malleable iron, allow railroads to convert from the high-friction bushing type to the economical and modern roller bearing on freight cars.

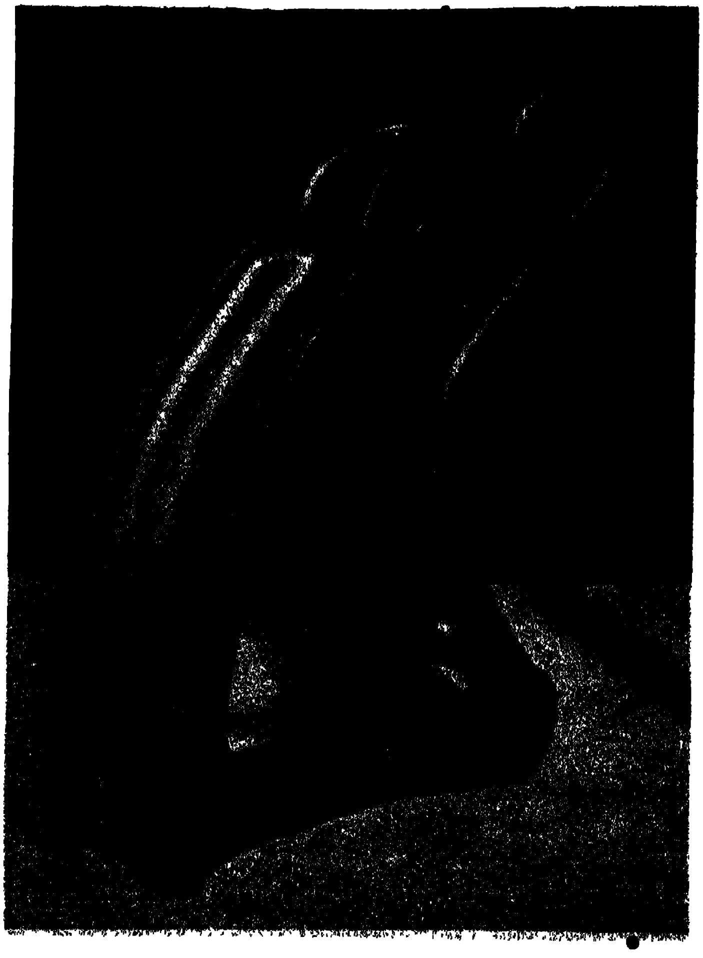


Fig. 20. Hand brake parts on railroad cars utilize malleable iron. A typical example is this bell crank which is subjected to high torque when the brakes are applied.

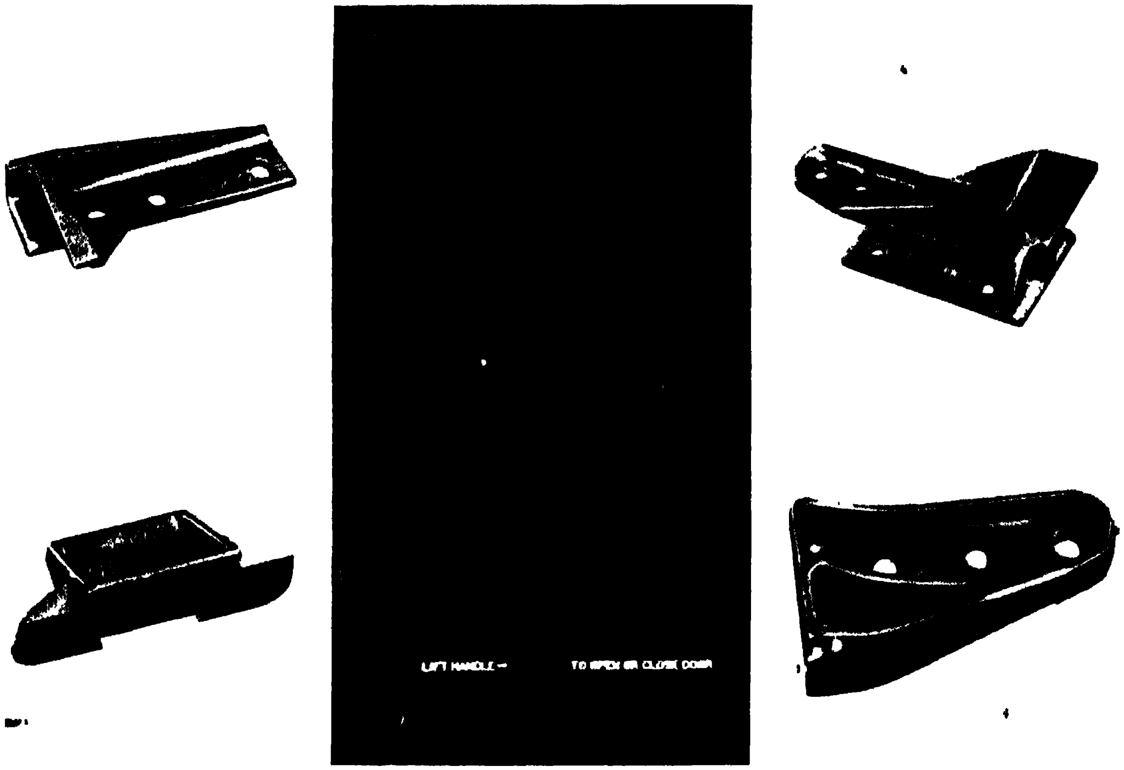
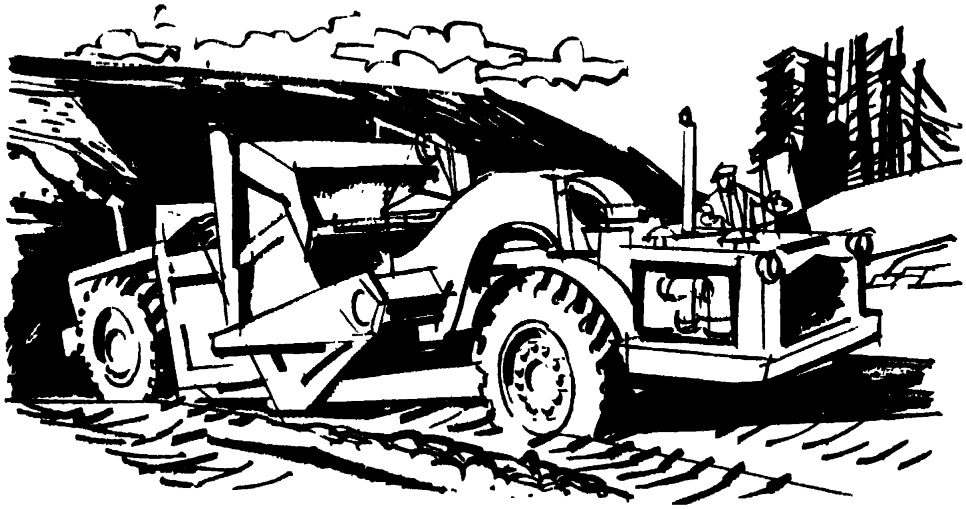


Fig. 21. **High impact and good corrosion resistance are important factors when choosing a material for parts such as these railroad door fixtures. Malleable iron is an outstanding choice to insure long service life.**

example of the railroad's dependence on malleable is illustrated by the hand brake parts, such as bell cranks. Railroad freight car doors employ a large number of malleable castings to good advantage.



Many types of malleable castings are used in the highway, heavy construction, and mining machinery industry. Gears, sprockets, levers, engine, and transmission parts are just a few typical examples. The manufacturer specifies malleable for the block of a sealed bearing used in a heavy duty tractor. This massive part is lubricated and sealed at the time of manufacture, hence wear resistance and the ability to withstand repeated jarring are of major importance.

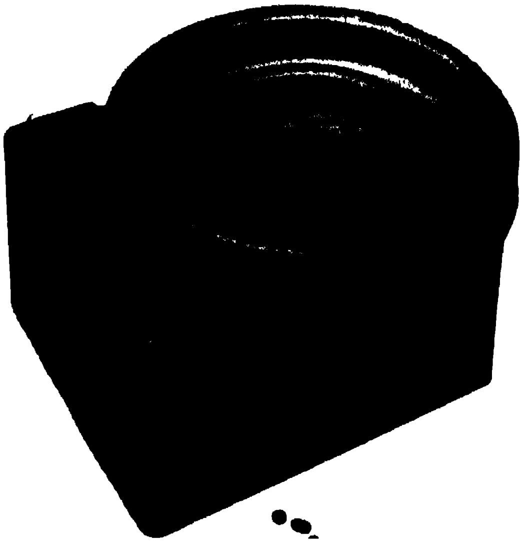


Fig. 22. Demanding service conditions and the ability to withstand continuous metal-to-metal wear were behind the choice of malleable for this 45.5-pound bearing block for a heavy-duty tractor. Section thicknesses approaching 3 inches form a well protected bed for a sealed-in bearing, which lasts the lifetime of the equipment.

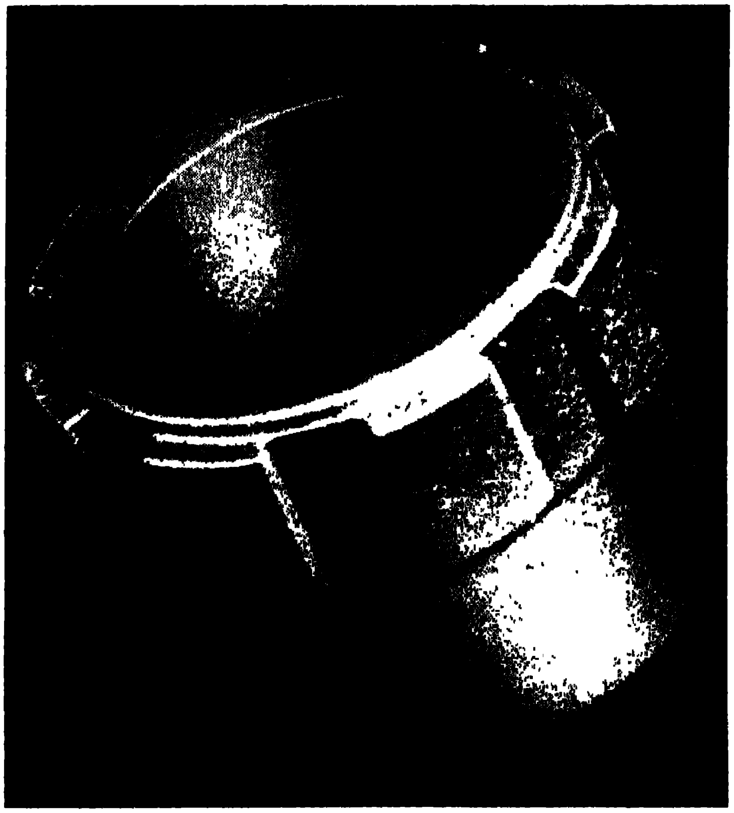
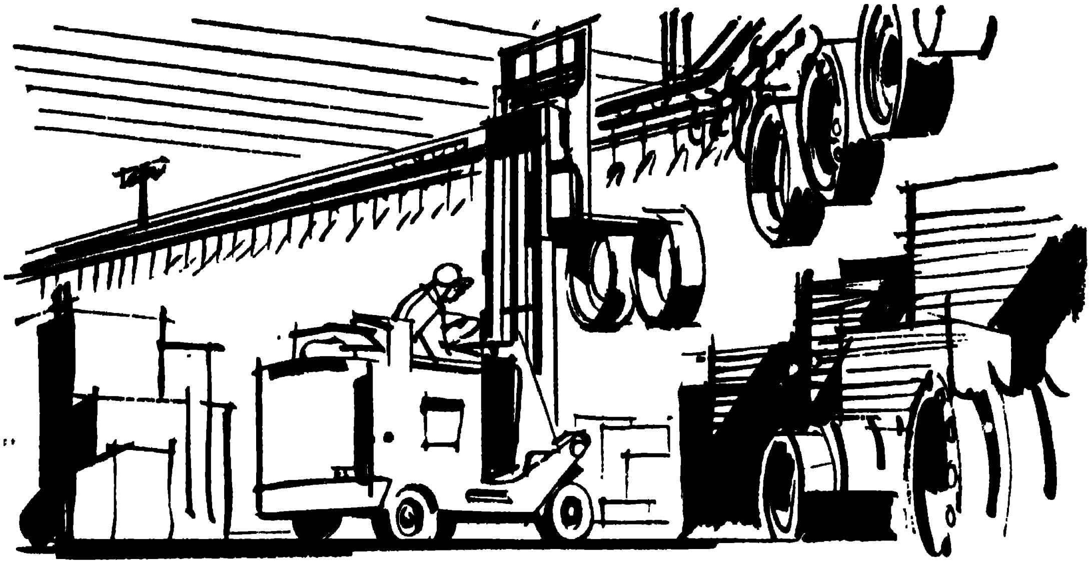


Fig. 23. Strength, hardness and toughness are combined in this pearlitic malleable drive shaft nut, used on a heavy duty tractor. Pearlitic malleable's excellent machinability contributes to the economy and peformance of the finished part.

Malleable iron expansion joints and bridge railing castings play an important part in the design and construction of highways.

Oil field equipment depends on malleable iron in vital components. Mine equipment uses many malleable iron parts. These parts must withstand the rigors of around-the-clock operation with dependability under extreme operating conditions.



In the industrial machinery and equipment industries, large tonnages of malleable iron are used. None of these relies on malleable more than the conveyor field, whether the installation requires the massive strength of the links for a multiple-strand log conveyor, or the tiny links shown earlier in this chapter. Chain hoist assemblies use malleable iron for a long life with minimum replacement and need for repair parts. Malleable's combination of wear resistance and reliability is recognized by the manufacturers of passenger elevators who specify it for such parts as roller guide stands. Axle housings for lift trucks are also made of malleable. These parts must have the strength and toughness that malleable affords. Of particular interest is the fact that a three-piece assembly was replaced by a one-piece malleable casting, which reduced the weight and finished part cost. Industrial casters are required to handle heavy loads and withstand rough usage, so malleable iron is specified.

Other applications of malleable iron in this general field take advantage of specific qualities of this material. Pearlitic malleable's response to selective surface hardening and its machinability mean lower costs and better service for gears, and often result in the elimination of machining operations.

Both standard and pearlitic malleable iron can be readily coined to close tolerances and to conformity. This results in reducing or eliminating machining operations. Examples are levers, rocker arms, crankshafts, gears, and sprockets.

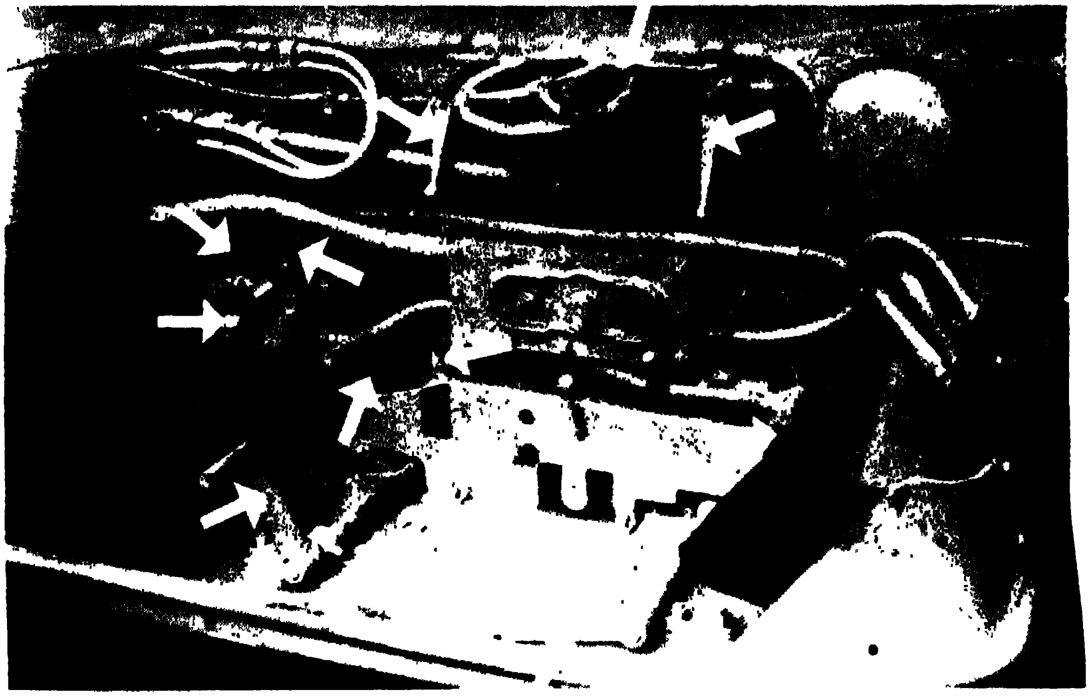


Fig. 24. Malleable iron parts, shown by the arrows, dependably serve in underground applications, such as this automatic continuous miner.

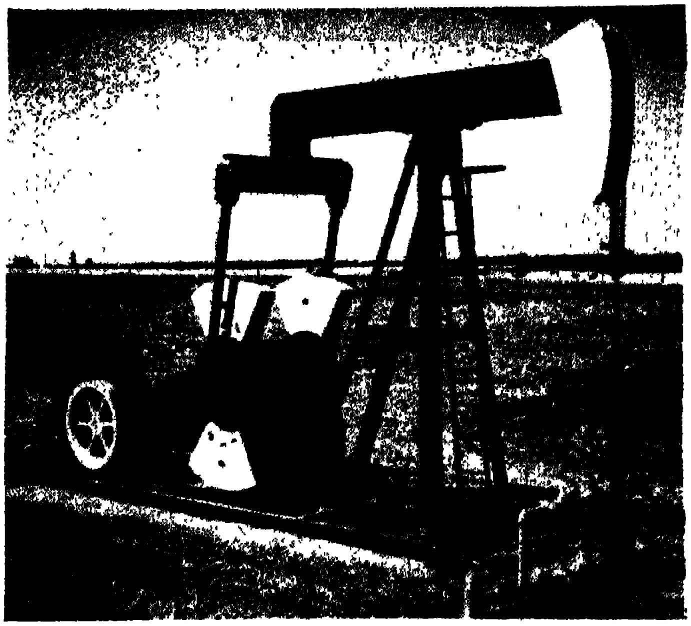


Fig. 25. This oil-field pump uses malleable iron in the gear reducer and brake mechanisms, for the lubrication pipe clamping device, in the saddle bearing assembly, on the center and end of the walking beam, and for the polished rod hanger.

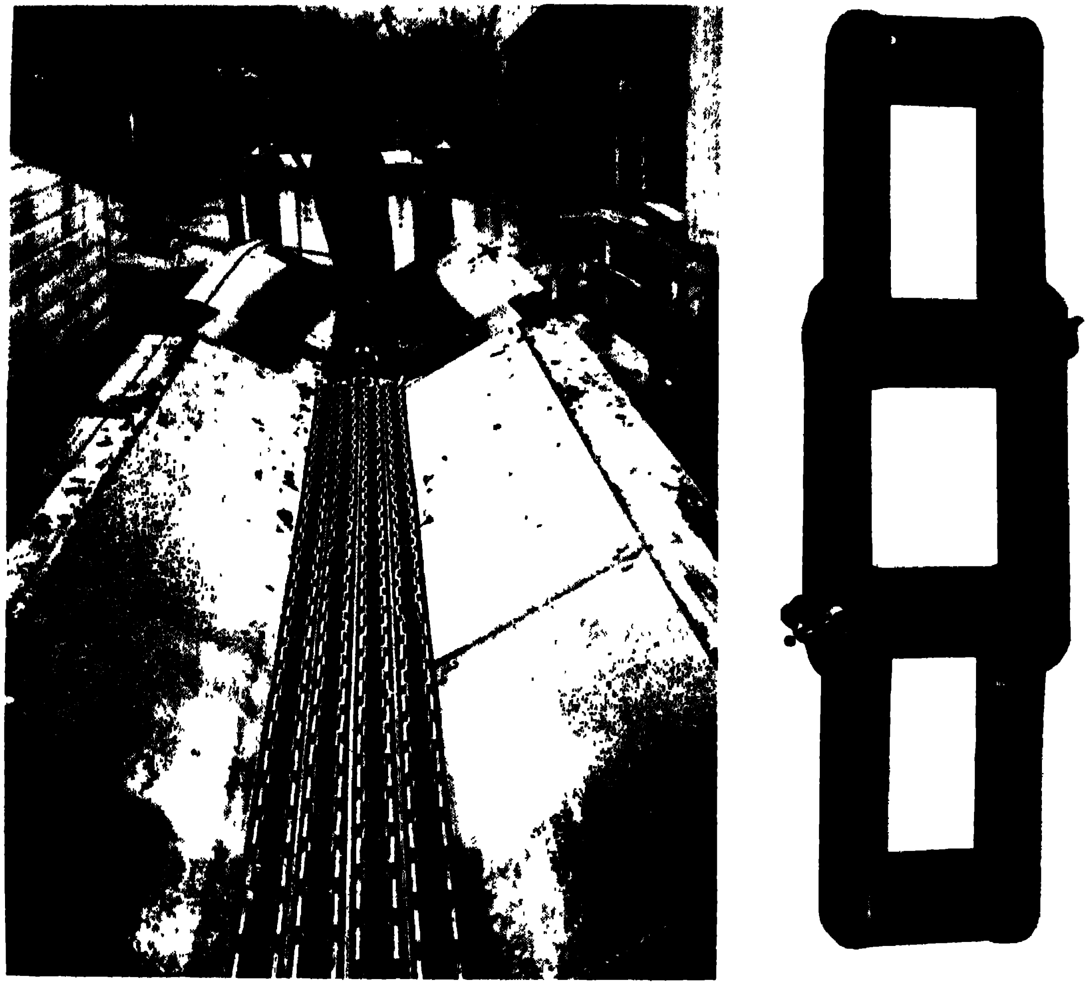


Fig. 26. Log conveyor chain links must stand up under bruising, battering service conditions. A strong, tough material is required, therefore malleable iron is commonly first choice.

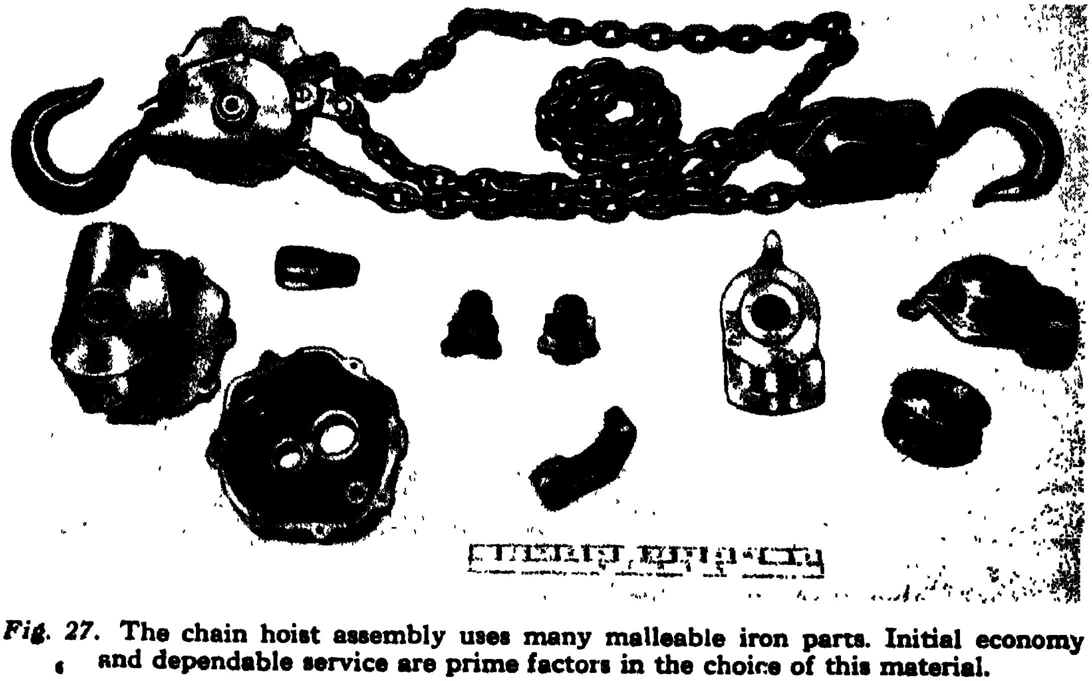


Fig. 27. The chain hoist assembly uses many malleable iron parts. Initial economy and dependable service are prime factors in the choice of this material.

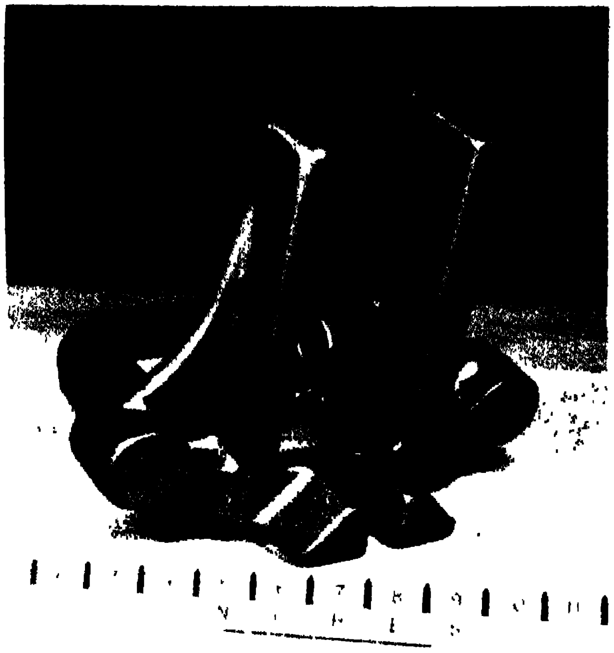


Fig. 28. This roller guide stand is used in passenger elevators. The complex shape of this part would make it difficult to produce except by the casting process. By combining the advantages of a casting and strong, tough malleable iron, the manufacturer achieves the ultimate in passenger safety.

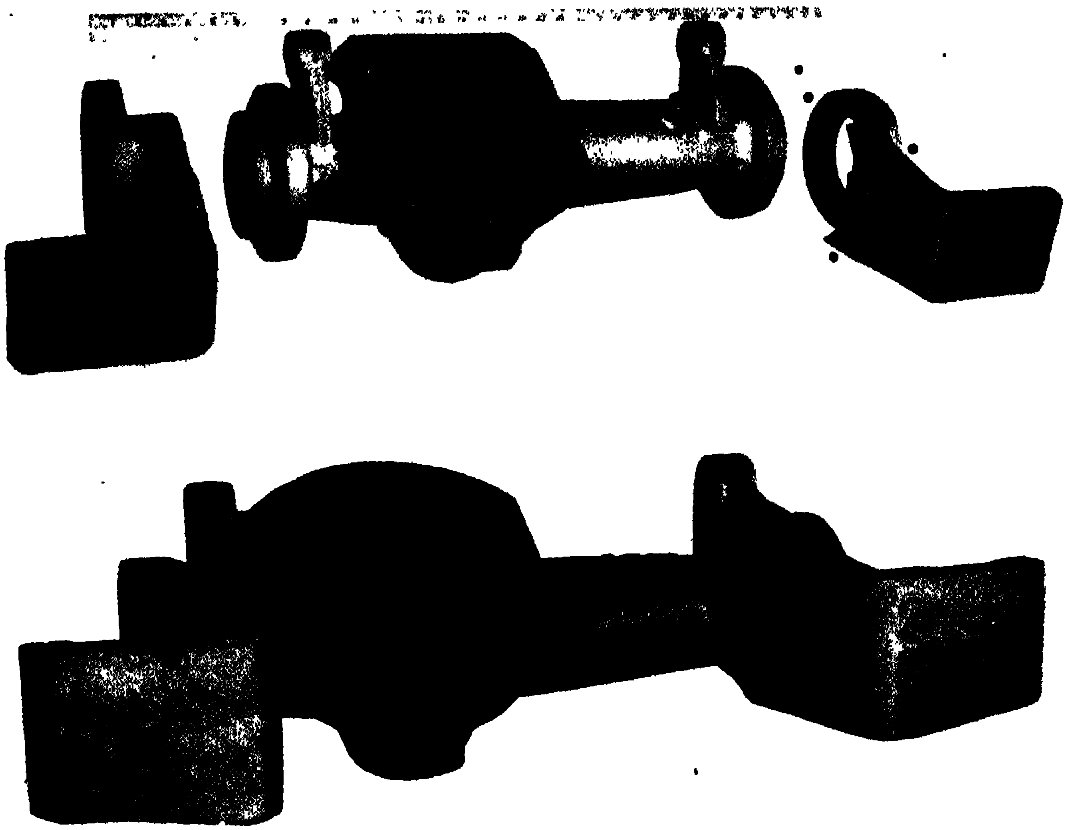


Fig. 29. This lift-truck axle housing is typical of the ways malleable iron provides economy and rugged dependability. The 3-piece assembly (above) was expensive to machine to close tolerances for assembly. Now, cast in one piece (below), this part is lighter, stronger and more economical to make.

In the plumbing and pipe fitting field, malleable iron castings are in common use. Soundness, ductility, machinability and castability are the properties responsible for the use made of malleable in this industry.

Pole line hardware for electrical transmission and distribution line fittings demands strength and dependability. Hence, malleable iron is widely utilized. It is also used for electrical conduit fittings and parts. The refrigerator and appliance field has many malleable iron and pearlitic applications, as do garden implements and lawnmowers. Some of the more common types are legs, brackets, frame parts, gears, handles, clamps, coin boxes for metered appliances, hinges, levers, connecting rods, bearing housings and couplings. Strength, economy, toughness, and corrosion resistance play an important part in all these applications.

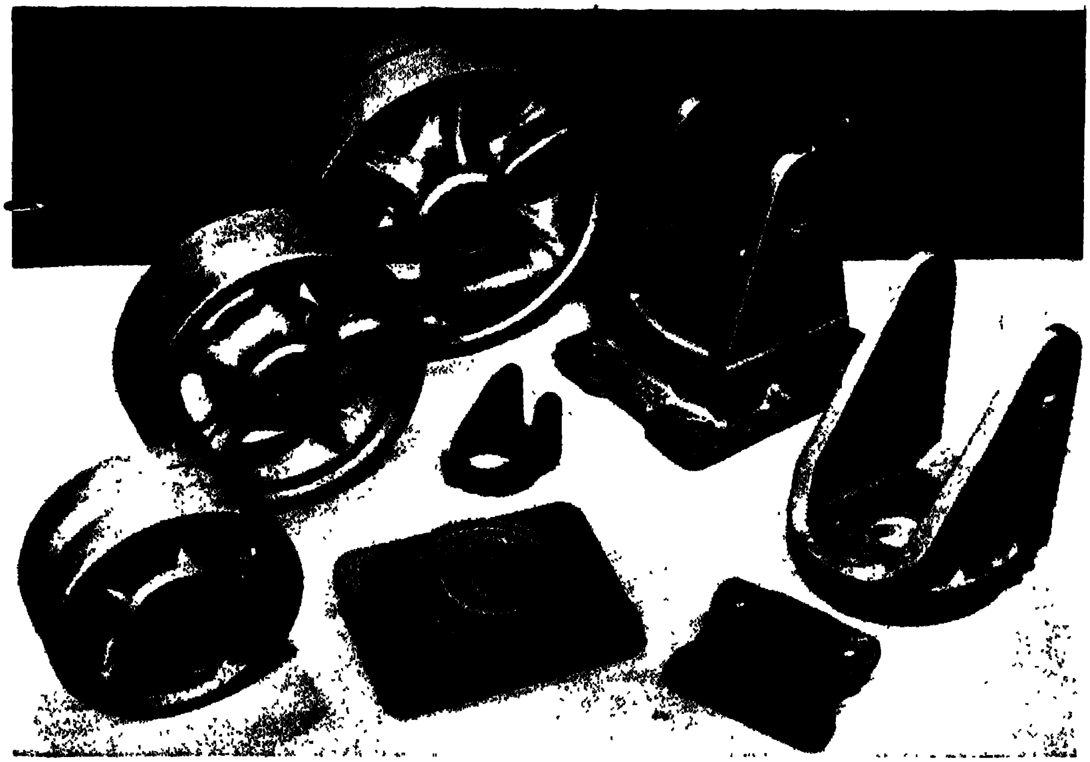


Fig. 30. **Subject to constant abuse, industrial casters, components of which are shown here, are a natural application for the many benefits available in malleable castings.**

Perhaps the most outstanding example of malleable's strength and toughness are the crankshafts used in pumps and small internal combustion engines. Excellent machinability—thus assuring reasonable cost—is one of the important reasons for the use of malleable iron castings in transmissions of automatic washing machines.

Malleable iron finds many kinds of applications in general hardware, tools and implements, particularly where a clean cast finish is desirable. Loadbinders, to hold heavy loads safely on trucks and railroad flat cars are economically cast of malleable iron. Door check assemblies illustrate the excellent appearance of malleable iron, giving the manufacturer a truly attractive product. The hand twist drill frame is another example of fine cast finish of malleable iron castings.

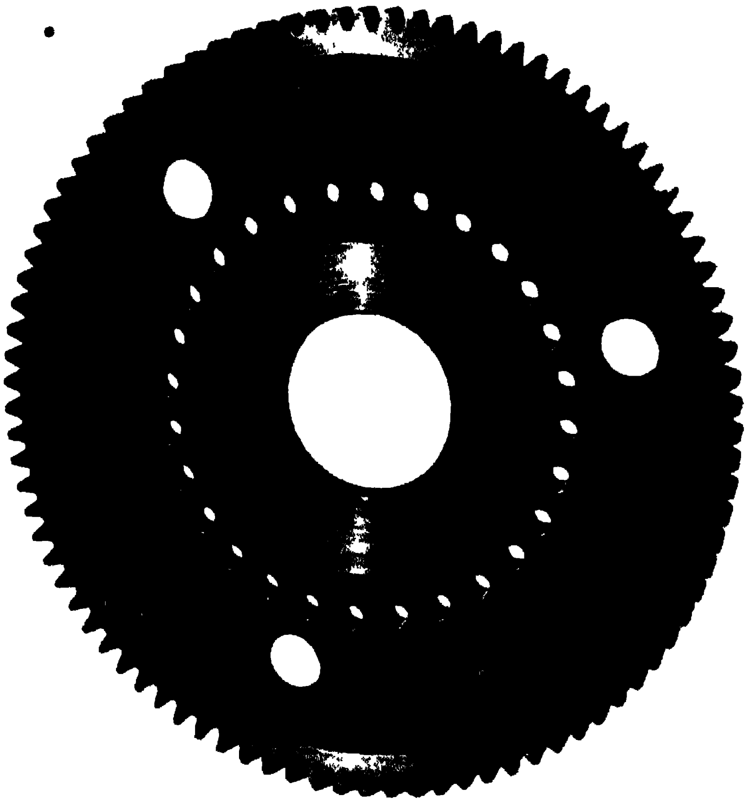


Fig. 31. This pearlitic malleable bull gear provides more than the necessary strength, while reducing machining cost over the former material. Malleable's ease of machining eliminated an expensive deburring operation formerly necessary in producing this part.

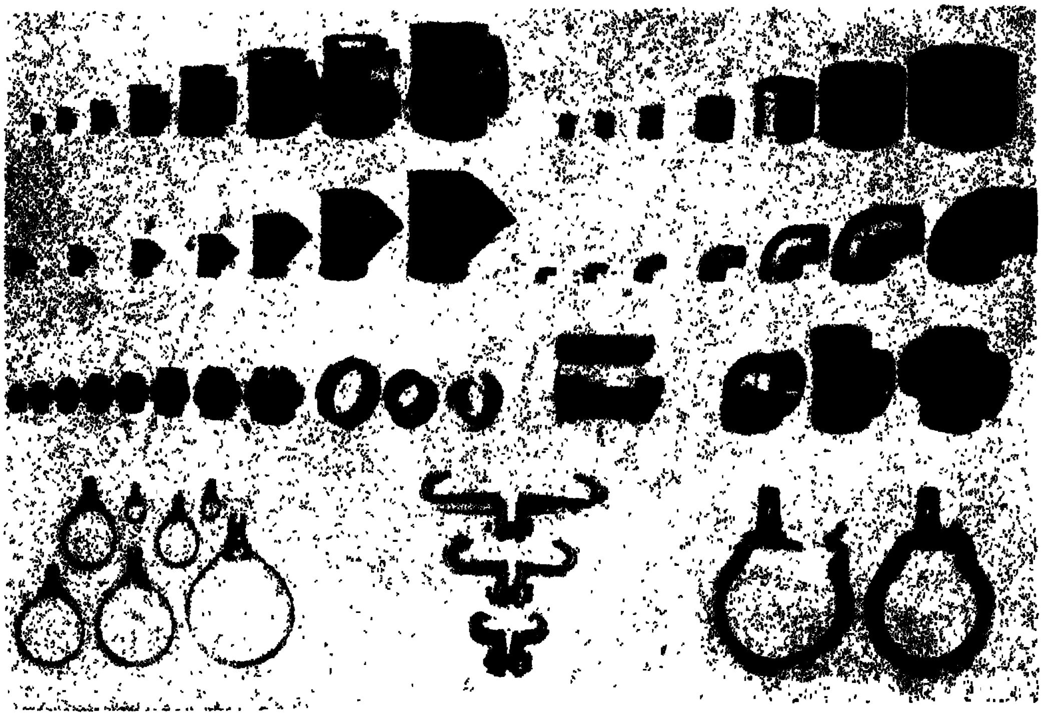


Fig. 32. Malleable iron is a natural choice for plumbing parts such as these pipe fittings and pipe hangers. Soundness, castability and ductility are the properties responsible for this use. Ease of machining contributes production economies.

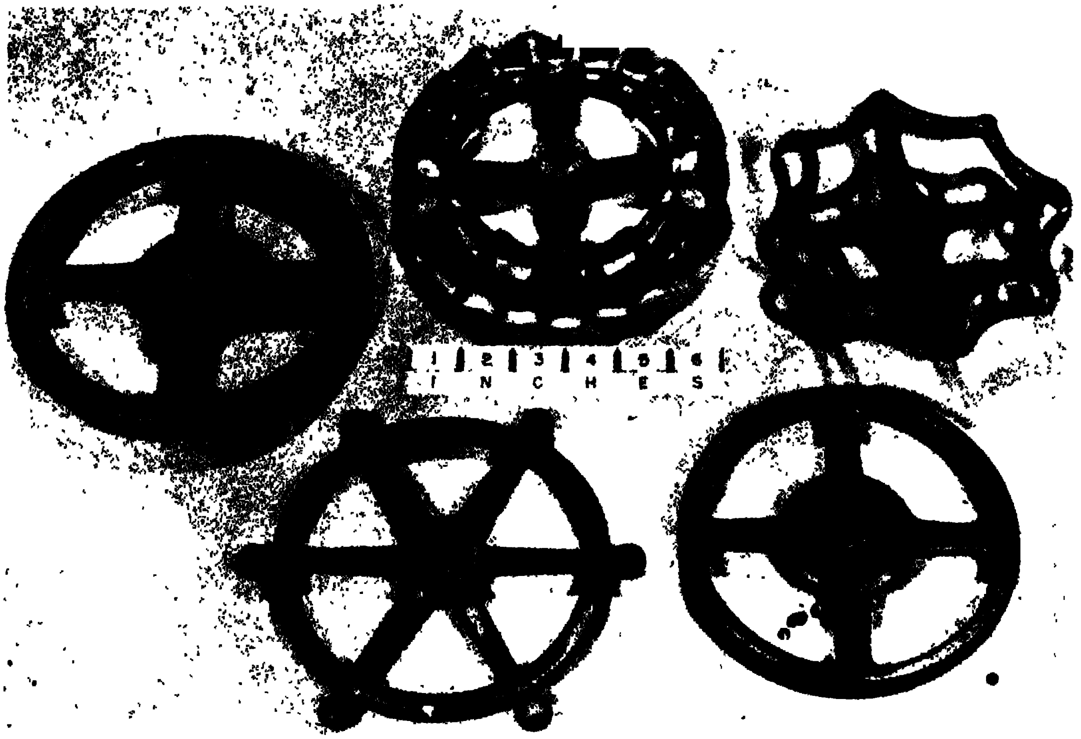


***Fig. 33.* Valve hand wheels, such as these shown here, illustrate the castability of malleable iron.**

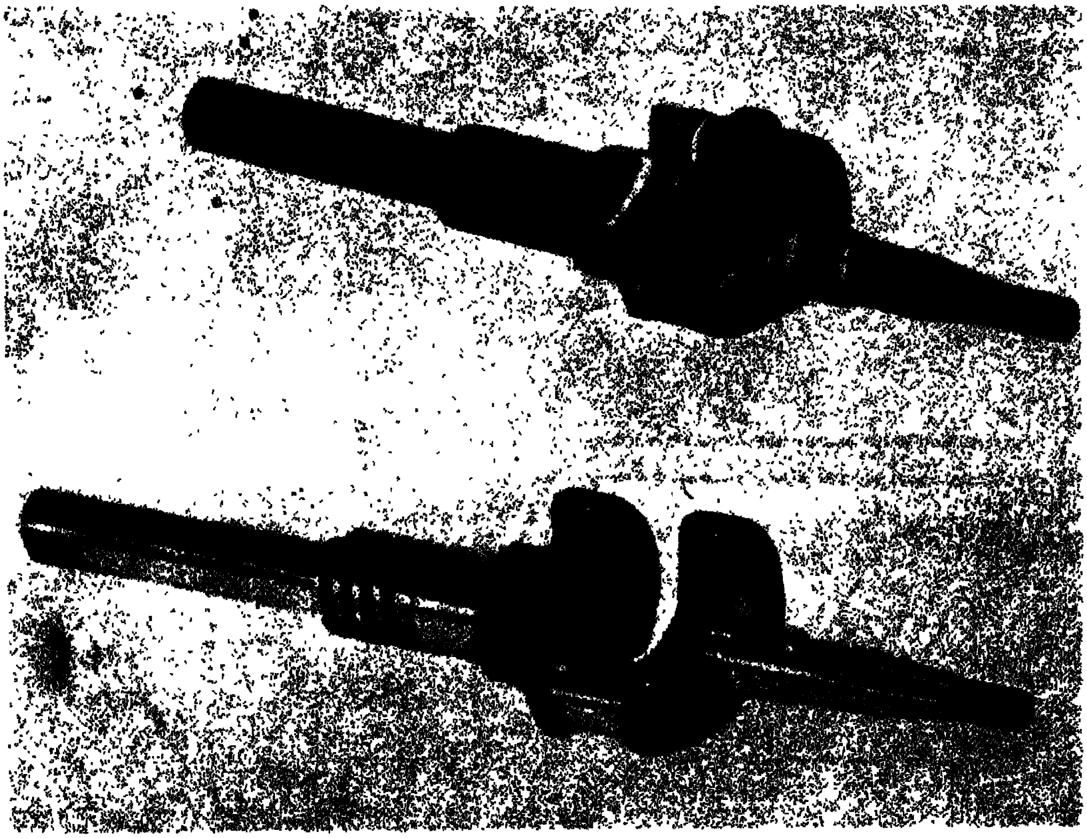


***Fig. 34.* Small engine crankshaft. This 3-pound casting, shown "rough" (top) and "finished" (bottom), is one example of pearlitic malleable parts used by the appliance industry. Initial economy, plus ease of machining, combine with malleable's inherent uniformity to produce a superior part.**

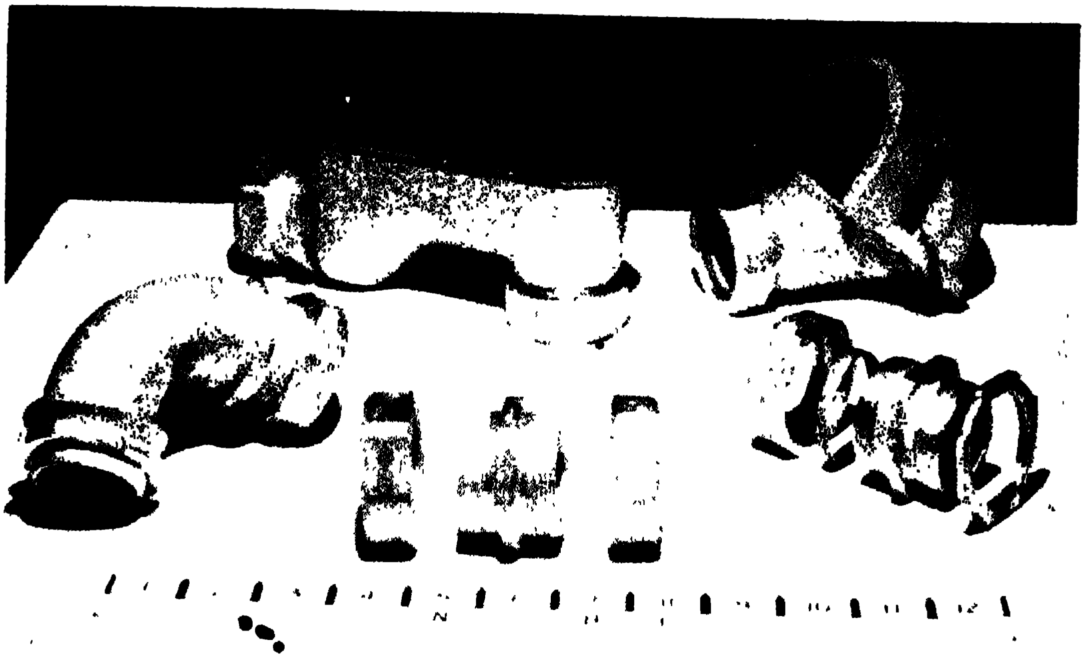


Fig. 35. Electric distribution systems utilize standard malleable for conduit fittings such as these bodies, nuts and rings.

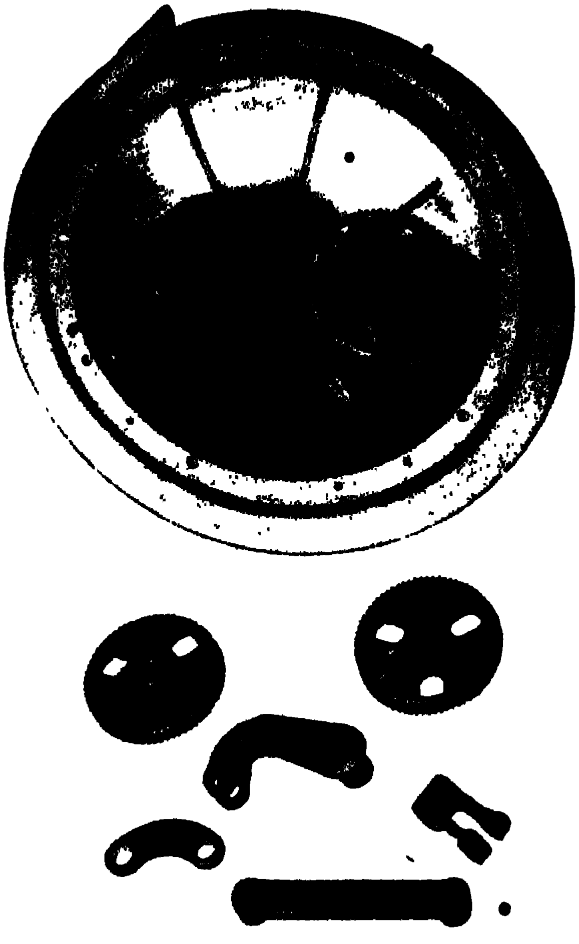


Fig. 36. In the home appliance field, malleable iron is a natural choice for gears, arms, levers and brackets, such as the parts shown here as used in an automatic washing machine transmission.

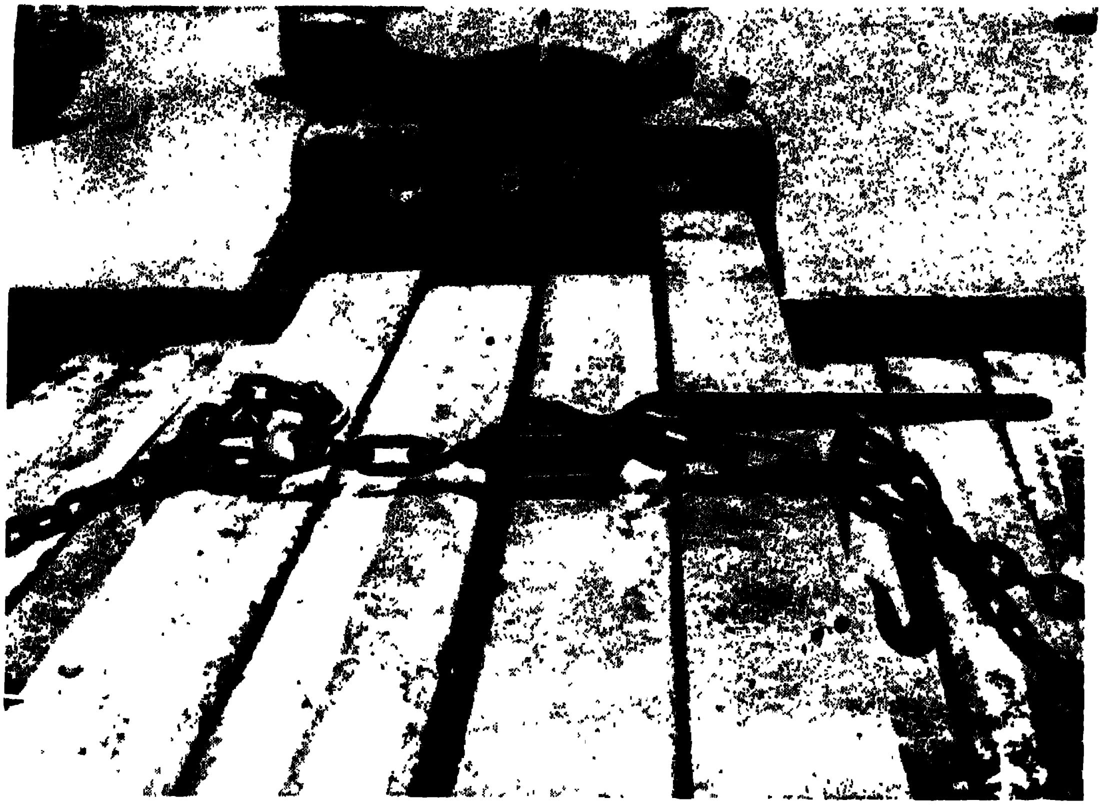


Fig. 37. Safety, strength, and economy are factors which dictate the choice of malleable for these loadbinder parts.

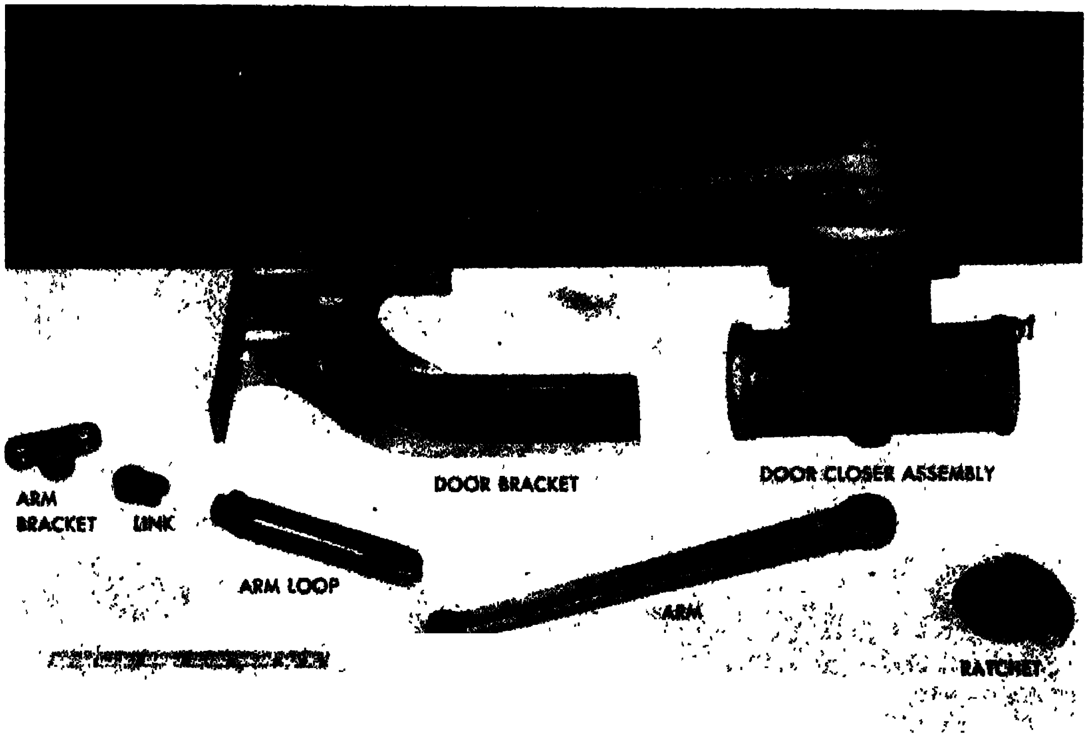


Fig. 38. This door closer assembly illustrates one of the many end-use applications of malleable iron. The fine cast finish permits malleable to be used "as is" for many similar parts.

Fig. 39. The hardware industry uses malleable iron castings, an example of which is this hand twist drill frame shown here. Little or no finishing is required, since malleable castings have good "eye appeal" for over-the-counter sales.

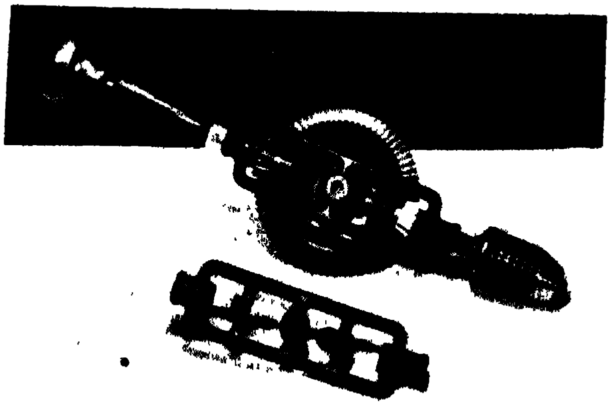
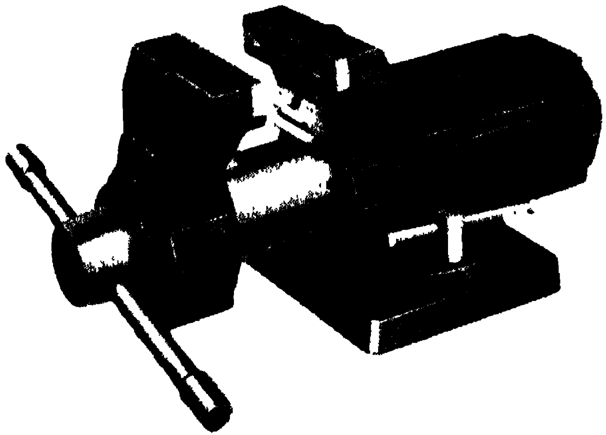


Fig. 40. Malleable iron's shock and impact resistance allow the manufacturer to guarantee this vise against breakage.



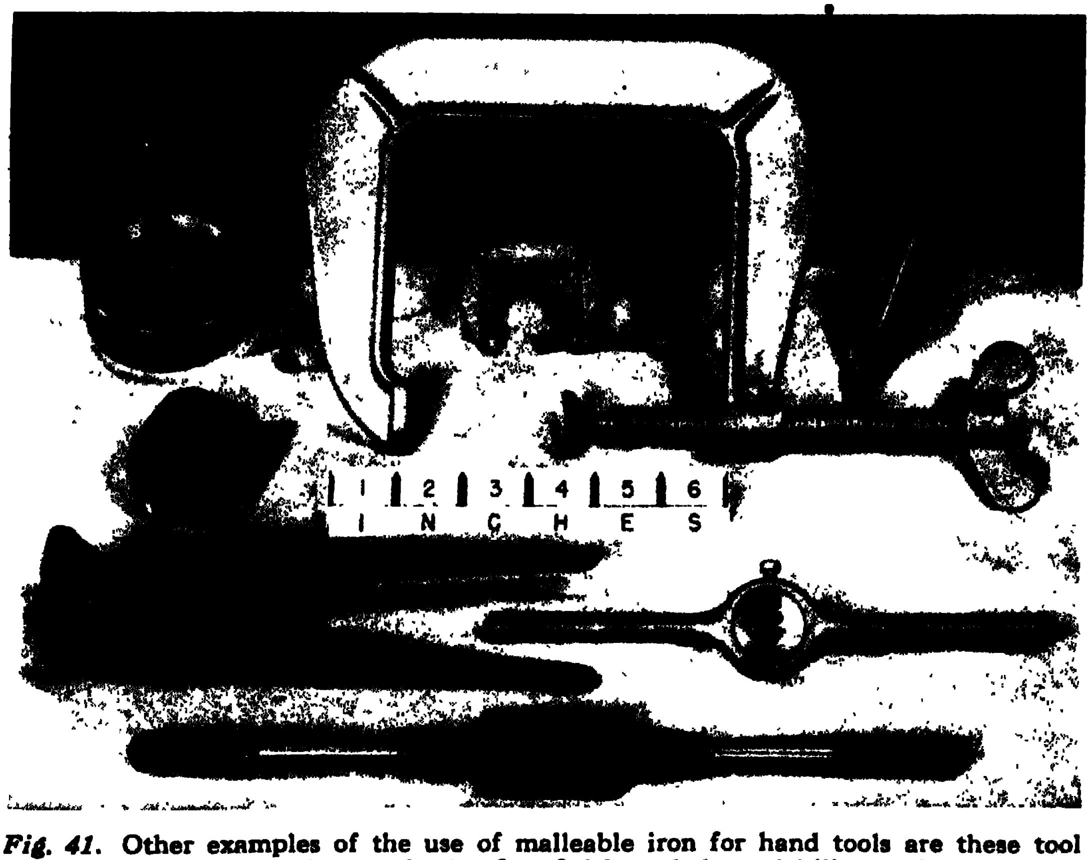


Fig. 41. Other examples of the use of malleable iron for hand tools are these tool holders, reamers, and clamps. Again, fine finish and dependability make malleable iron first choice in this field.

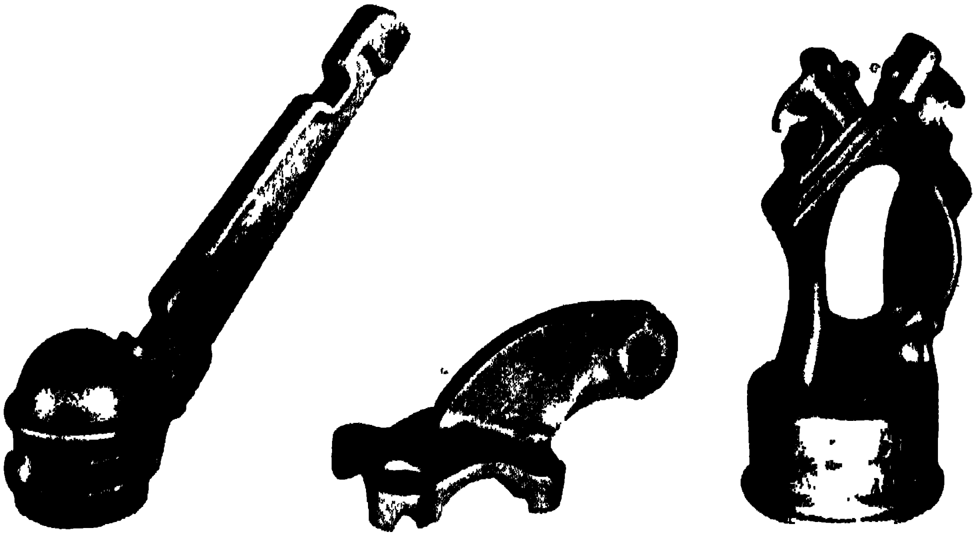


Fig. 42. Malleable iron castings used as fence fittings.

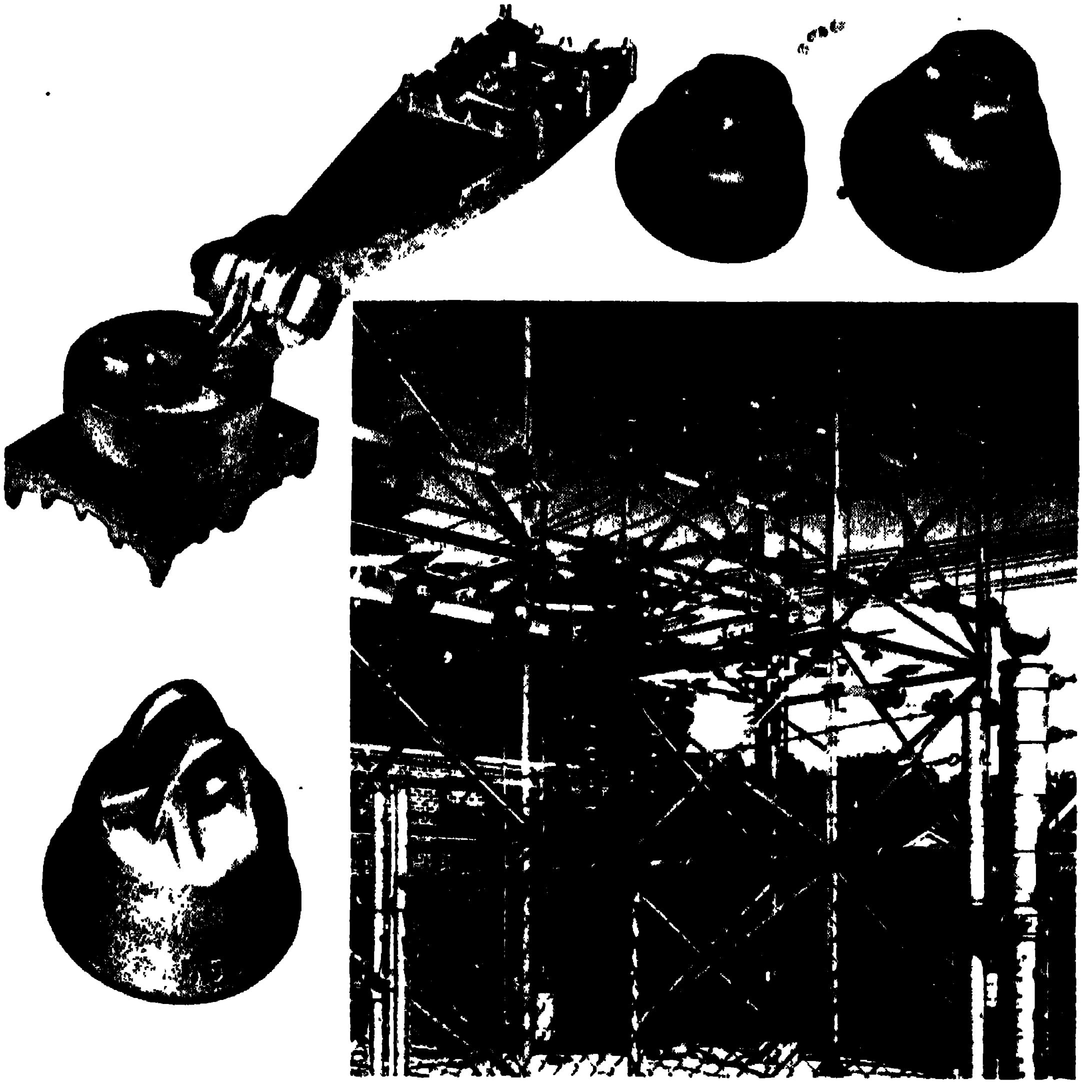


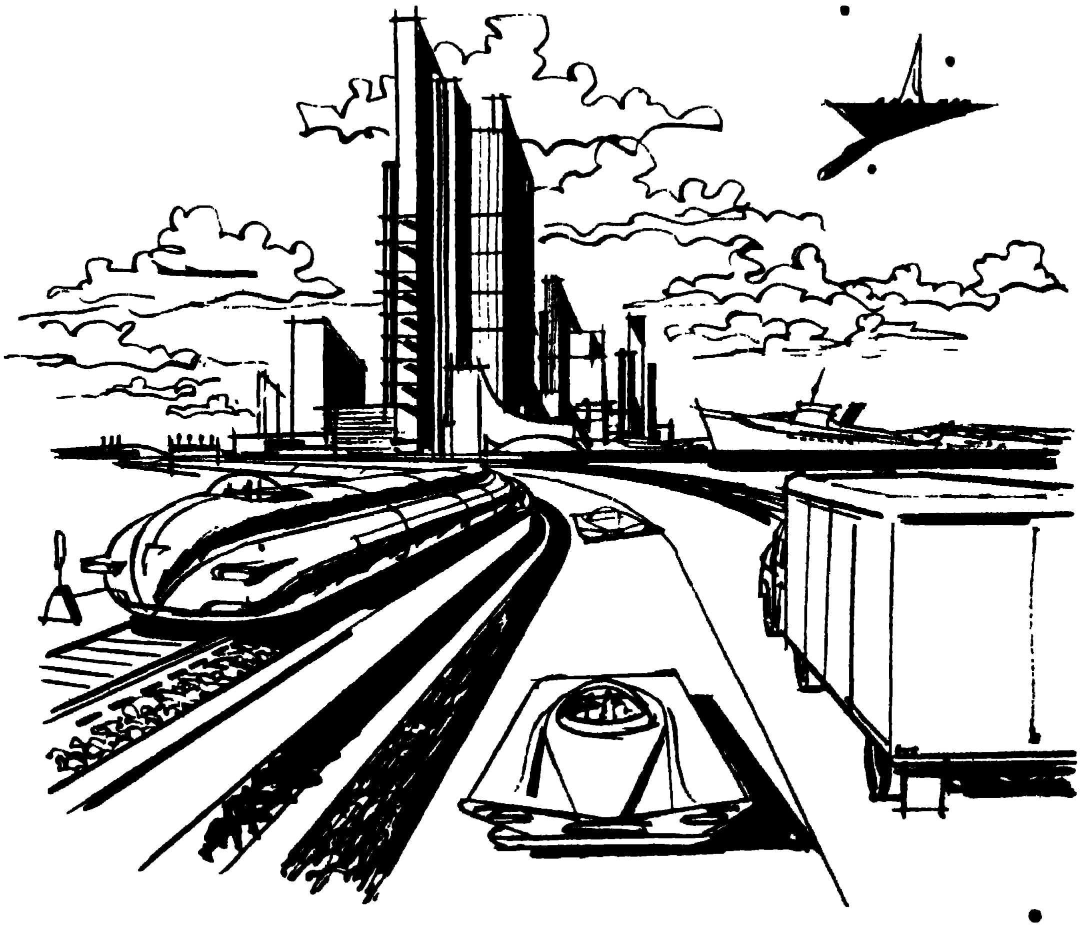
Fig. 43. Malleable iron castings are used extensively as fittings for electrical transmission and distribution lines.

In small hand tools, where strength is clearly important, malleable iron is widely used. Strength plus high shock resistance, available in malleable iron, enables one vise manufacturer to guarantee his line of malleable iron vises against breakage during the life of the product. All the machinists' vises in this line, which have built-in anvils, are warranted to stand up under the repeated shock of heavy hammer blows in regular use.

Many hardware parts must withstand the tests of time and corrosion. Resistance to atmospheric corrosion is important in such parts as the pole line hardware already mentioned, fence fittings and boat fittings. In these applications, malleable's ready receptivity to galvanizing and other protective coatings is employed to provide better protection against corrosion.

Defense requirements call for large tonnages of malleable as components for ground-support equipment, for missiles and aircraft, tanks, special-purpose vehicles, and shells.

This chapter has shown a few of the many advantages malleable iron delivers to its users day after day. In our rapidly changing economy, manufacturing practices do not long remain static; what is impossible today will be routine tomorrow. New tools, improved techniques and other operating practices engender constant change. The producers of malleable iron castings carry on a never-ending program to provide still better parts at lower cost.



III

THE PRODUCTS OF THE MALLEABLE CASTINGS INDUSTRY

Malleable iron is often categorically referred to as though it were a single product, all of one class or grade, when in fact three classes and numerous grades with wide ranges of mechanical and engineering properties are regularly manufactured. All the classes and grades, as well as methods of manufacture, will be discussed in other chapters. The aim of this chapter is to offer a bird's-eye view of what the industry makes, pointing out the special properties which fit the various classes and grades of malleable iron for specific uses. Described in summary fashion, malleable iron meets exacting requirements of strength, toughness, machinability, and impact resistance, and possesses the valuable combination of castability and malleability.

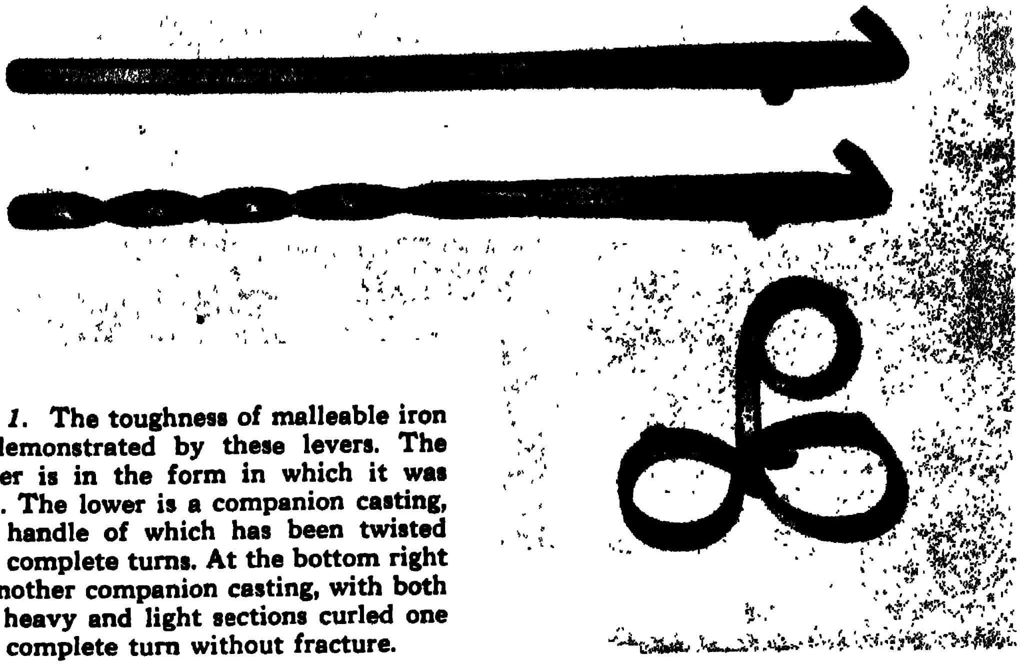


Fig. 1. **The toughness of malleable iron is demonstrated by these levers. The upper is in the form in which it was cast. The lower is a companion casting, the handle of which has been twisted two complete turns. At the bottom right is another companion casting, with both the heavy and light sections curled one complete turn without fracture.**

Of the three classes of malleable iron, two are of principal importance. These are, first, standard malleable, which consists largely of ferrite interspersed by nodules of free carbon, is manufactured in two grades, and leads the field in production volume; and, second, pearlitic malleable, which contains some carbon in the combined form through special heat-treatment, through alloying or through both, is manufactured in several specification grades, and has rapidly increased in use during the past decade. A third class—alloyed malleable—is completely graphitized, having a ferritic matrix similar to that of standard malleable iron, and owes its somewhat higher strength to its alloy content. Cupola malleable, though still covered by A.S.T.M. Specification A 197-47, has been almost completely supplanted by the other classes.

In the manufacture of malleable iron, the raw materials—pig iron, sprue or remelt, and scrap—are melted and refined under carefully controlled conditions, and the molten metal is poured or "cast" into suitable molds, generally of sand. The cast metal is the basic material from which all malleable products are made. Because of its steely white fracture, this is known as "white iron"; since it is extremely hard and brittle, it is also sometimes called "hard iron." Its property of hardness leads to white iron's being used as a specialty product in certain applications. The next step in manufacture is the conversion of the white iron into the final product by an accurately controlled heat-treatment. In standard malleable iron this heat-treatment, commonly called annealing, converts the constituents of the initially cast white iron into soft, carbonless ferrite, through which are interspersed nodules of free carbon, often referred to as "temper carbon." In the manufacture of pearlitic malleable iron, the heat-treatment, the chemical composition, or both, are regulated in such a manner as to leave a predetermined amount of the carbon in the combined state, the amount varying with the hardness and tensile properties desired in the finished casting. After heat-treatment, the castings are cleaned, given such finishing operations as may be required, and then finally inspected.

The chemical composition of the white iron castings generally falls

TABLE 1. TYPICAL COMPOSITION RANGE OF MALLEABLE IRON, GRAY IRON, AND MEDIUM CARBON STEEL CASTINGS

	*Malleable Iron** (*white iron*)	*Gray Iron*	*Medium Carbon Steel*
Carbon, per cent	2.00-2.65	2.75-3.60	0.20-0.50
Silicon, per cent	1.40-0.90	2.90-0.65	0.20-0.80
Manganese, per cent	0.25-0.55	0.50-0.90	0.50-1.00
Phosphorus, per cent	Less than 0.18	0.10-0.80	Less than 0.05
Sulfur, per cent	0.05-0.18	0.06-0.12	Less than 0.06

*** The chemical composition of malleable iron is always expressed in terms of white-iron analysis.**

within the limits shown in Table 1, and may be compared there with the chemical makeup of gray iron and medium carbon steel castings.

CLASSES AND GRADES

Specifications for the classes of malleable iron in principal use—standard and pearlitic—with Brinell hardness number ranges for pearlitic grades are given in Table 2, where they may be readily compared:

STANDARD MALLEABLE IRON

Standard malleable castings have high toughness and ductility and excellent machinability, with good damping capacity and resistance to atmospheric corrosion. Specification A 47-52 of the American Society for Testing Materials covers two grades of standard malleable iron.

Grade 32510 standard malleable iron is produced from white iron castings whose chemical composition generally falls within the following limits:

	Per Cent
Carbon	2.30 to 2.65
Silicon	1.40 to 0.90
Manganese	0.25 to 0.55
Phosphorus	Less than 0.18
Sulfur	0.05 to 0.18

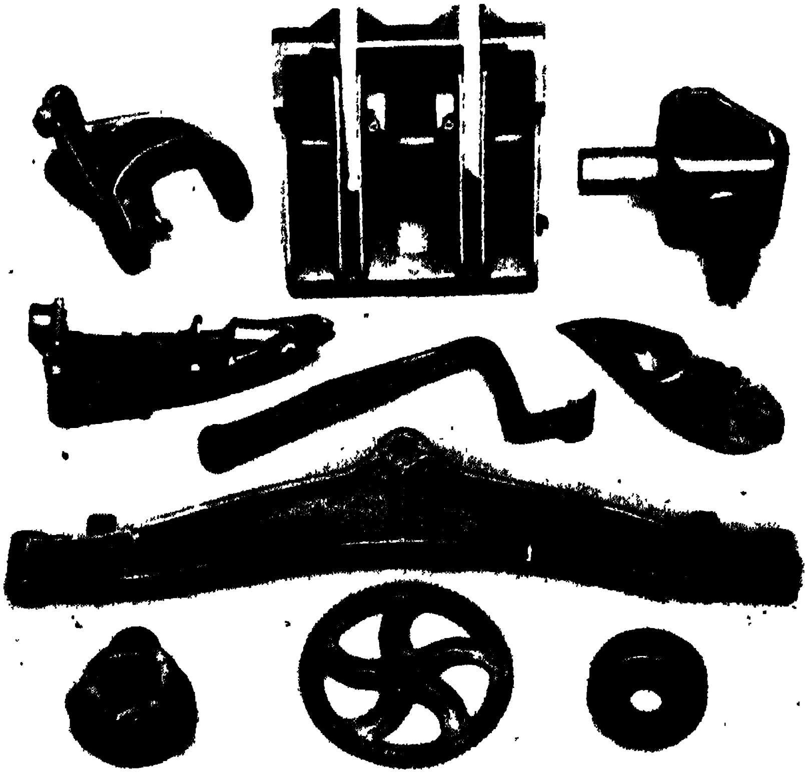


Fig. 2. A typical group of agricultural implement castings.

TABLE 2. SPECIFICATIONS FOR STANDARD AND PEARLITIC MALLEABLE IRON

STANDARD MALLEABLE IRON

Specifying Group	Number	Grade	Minimum Tensile Strength p.s.i.	Minimum Yield Point† p.s.i.	Minimum Elongation % in 2"	Brinell Hardness Number Range
American Society for Testing Materials	A 47-52	32510	50,000	32,500	10	
	A 47-52	35018	53,000	35,000	18	
Society of Automotive Engineers		32510	50,000	32,500	10	
		35018	53,000	35,000	18	
Association of American Railroads	M 402-48	35018	53,000	35,000	18	
American Standards Association	G 48.1-1953 UDC 669.13	Same as A.S.T.M.				
American Ass'n State Highway Officials	M-106	Same as A.S.T.M.				
A.S.M.E. Boiler Construction Code	SA-47	Same as A.S.T.M. *(Grade 35018 only)*				
Federal Supply Service General Services Admin. for all Federal Agencies U.S. Dept. of the Army U.S. Dept. of the Navy	QQ-I-666c	I (35018)-Black ungalvanized	53,000	35,000	18	
		IG (35018)-Zinc coated galvanized	50,000	32,500	14	
		II (32510)-Black ungalvanized	50,000	32,500	10	

PEARLITIC MALLEABLE IRON

Specifying Group	Number	Grade	Minimum Tensile Strength p.s.i.	Minimum Yield Point† p.s.i.	Minimum Elongation % in 2"	Brinell Hardness Number Range
A.S.T.M.	A 220-55T	45010	65,000	45,000	10	
		45007	68,000	45,000	7	
		48004	70,000	48,000	4	
		50007	75,000	50,000	7	
		53004	80,000	53,000	4	
		60003	80,000	60,000	3	
		80002	100,000	80,000	2	
S.A.E.	. . . . . .	43010	60,000	43,000	10	
		48005	70,000	48,000	5	
		53004	80,000	53,000	4	
		60003	80,000	60,000	3	
		70002	90,000	70,000	2	
S.A.E.	AMS 5310B‡	. . .	70,000	48,000	5	179-229
U.S. Dept. of the Army-Ordnance Division Military Specification U.S. Dept. of the Navy Federal Specification	MIL-I-11444					
	Class 1	(70002)	90,000	70,000	2	241-285
	Class 2	(60003)	80,000	60,000	3	197-241
	Class 3	(53004)	80,000	53,000	4	197-241
	Class 4	(48005)	70,000	48,000	5	179-228
	Class 5	(43010)	60,000	43,000	10	163-207

† Use Yield Point or Yield Strength as applicable.

‡ Aeronautical Materials Specification.

TABLE 3. TYPICAL BRINELL HARDNESS RANGES

Specifying Group	*Number*	*Grade*	*Typical Brinell Hardness Number Range*
A.S.T.M.	A 220-55T	45010	163-207
		45007	163-217
		48004	163-228
		50007	179-228
		53004	197-241
		60003	197-255
		80002	241-269
S.A.E.	....	43010	163-207
		48005	179-228
		53004	197-241
		60003	197-241
		70002	241-285

Grade 32510 generally has the higher carbon content of the two grades of standard malleable iron. It is extremely fluid and for this reason is very well suited to castings of light section, intricate design, or both. Foundries which specialize in very light work are producing castings of this grade of malleable iron with sections as light as 1/32 inch in limited areas. Grade 32510 can also be specified for castings exceeding 1½ inches in thickness. Malleable iron is noted for the ease with which it is machined, and it is this factor which prevails in the selection of Grade 32510 rather than other ferrous products for many applications. The automotive, agricultural implement, and electrical industries utilize a large proportion of the Grade 32510 metal produced.

Grade 35018 standard malleable iron is produced from white iron castings of chemical composition generally within the following ranges:

	Per Cent
Carbon	2.00 to 2.45
Silicon	1.25 to 0.95
Manganese	0.25 to 0.55
Phosphorus	Less than 0.18
Sulfur	0.05 to 0.18

Grade 35018, because of its lower carbon content, has somewhat higher strength and notably higher ductility than Grade 32510, and is usually selected for applications requiring these properties. Its impact resistance, or ability to withstand shock, is high. Malleable iron of this grade is regularly being cast in sections from 3/32 to 2½ inches and upon occasion in even larger sections. Grade 35018 malleable castings are also readily machined. Typical applications are railroad castings, high-pressure castings, and oil-field castings.

Standard malleable iron is often specified for applications comparable to those for which steel castings with between 0.20 and 0.30 per cent *carbon and drop forgings with between 0.10 and 0.30 per cent carbon are* used. The yield point of such steels varies between 45 and 60 per cent of the tensile strength, depending on type; for standard malleable iron the ratio of yield point to minimum tensile strength is approximately 65 per cent.

The relation between tensile strength and elongation is another property of extreme importance to the designer. In some metals, strength and ductility vary inversely, the metal becoming harder and less ductile as its strength increases. When using such metals, therefore, the designer must decide whether strength or ductility is the more important for a particular application, and then sacrifice one to obtain the other. Standard malleable iron does not impose this limitation; in it, the high tensile strength is accompanied by higher elongation.

The graphitized structure of malleable iron is uniform throughout the casting. Thickness of section hence is no barrier to thoroughness of the heat-treatment, for graphitization is an internal phenomenon occurring throughout the metal when the graphitizing temperature has been reached. Whatever slight decarburization may occur is limited to the very surface of the casting.

PEARLITIC MALLEABLE IRON

The pearlitic malleable irons owe their desirable properties of higher strength, hardness, fatigue life, and excellent resistance to abrasive wear primarily to their combined carbon content. They respond readily to hardening treatments applied to the surface, to selected areas, or to the entire structure, and this fact has extended their use substantially. In addition, they offer the designer a valuable combination of rigidity, moderate ductility, and ready machinability. As with standard malleable, the pearlitic malleable irons are cast in a wide range of section thicknesses. They have for these reasons been adopted for many installations where high-strength steel components had earlier been used.

A.S.T.M. Specification A 220-55T, as listed in Table 2, recognizes seven grades of pearlitic malleable. They differ among each other principally in the quantity of combined carbon (ranging from 0.3 to 0.9 per cent carbon), and the form in which it is present as a result of special heat-treatment or alloying. Pearlitic malleable castings are extensively used in the automotive and agricultural equipment industries, and in ordnance materiel.

ALLOYED MALLEABLE IRON

Copper and molybdenum are the chief alloying elements used in the manufacture of alloyed malleable irons for special applications. Save for the addition of the alloying elements, the manufacturing process for these irons is the same as that for standard malleables. Their special properties are due to the effect of the alloy on the matrix of the castings, which is usually ferritic.

Copper-alloyed malleables contain from about 0.25 to 1.25 per cent copper. Adding from 0.25 to 0.50 per cent copper to standard malleable compositions increases resistance to atmospheric corrosion, particularly in sulfurous atmospheres. If larger amounts of copper are added, tensile strength and yield point are raised, and elongation is slightly reduced. A precipitation-hardening treatment will further increase the strength of such irons.

Malleables alloyed with copper and molybdenum give extra high strength with no appreciable reduction of ductility. Irons thus alloyed offer a minimum tensile strength of 58,000 to 65,000 p.s.i., minimum yield strength of 40,000 to 45,000 p.s.i., and minimum elongation of 15 to 20 per cent in two inches.

GENERAL CONSIDERATIONS

Nationally recognized specifications for malleable castings, such as those of the American Society for Testing Materials, the Society of Automotive Engineers, the United States Government agencies, and the Association of American Railroads, include minimum mechanical properties as well as requirements for good workmanship, soundness of structure, and trueness to pattern. Chemical limits are not specified, because the mechanical properties desired are obtainable with various analyses and processes. Methods for performing tension tests, dimensions and preparation of test specimens, inspection procedure, and the like usually follow the A.S.T.M. standards very closely.

IV

PHYSICAL PROPERTIES OF STANDARD MALLEABLE IRON

The usefulness of an engineering material obviously is determined by its fundamental physical properties and its mechanical and engineering characteristics. Though at one time the physical properties of a metal were taken as including both physical and mechanical characteristics, the term has been restricted, as knowledge has increased, to such properties as weight, volume, and thermal, electrical, and magnetic values. The physical properties of standard malleable iron will be surveyed in this chapter. Later chapters will refer to this discussion for similarities or differences in the physical properties of other classes of malleable iron.

WEIGHT

Weight is a measure of the force of gravity, specifically of the pull of gravitational forces on a body, and is proportional to the mass of the body, or in other words, the amount of matter which the body contains.

DENSITY

The density of a substance is the weight per unit volume, usually expressed in grams per cubic centimeter. The density of pure iron at room temperature, 68 degrees F., is 7.87 grams per cubic centimeter.[17] A decrease in density with increasing carbon and silicon is to be expected in iron-carbon alloys such as malleable iron. Differences in density may also result from different methods of processing, particularly for pearlitic malleable irons.

Density values of malleable iron constituents are given in Table 1.

TABLE 1. DENSITY OF MALLEABLE IRON CONSTITUENTS[17,22]

Iron (ferrite), pure	7.87 g/cc
Iron, 4 per cent silicon	7.60
Iron, 10.3 per cent silicon	6.97
Iron, 1 per cent silicon (interpolated from above data)	7.82
Graphite	2.25
Iron carbide	7.66
Pearlite	7.85

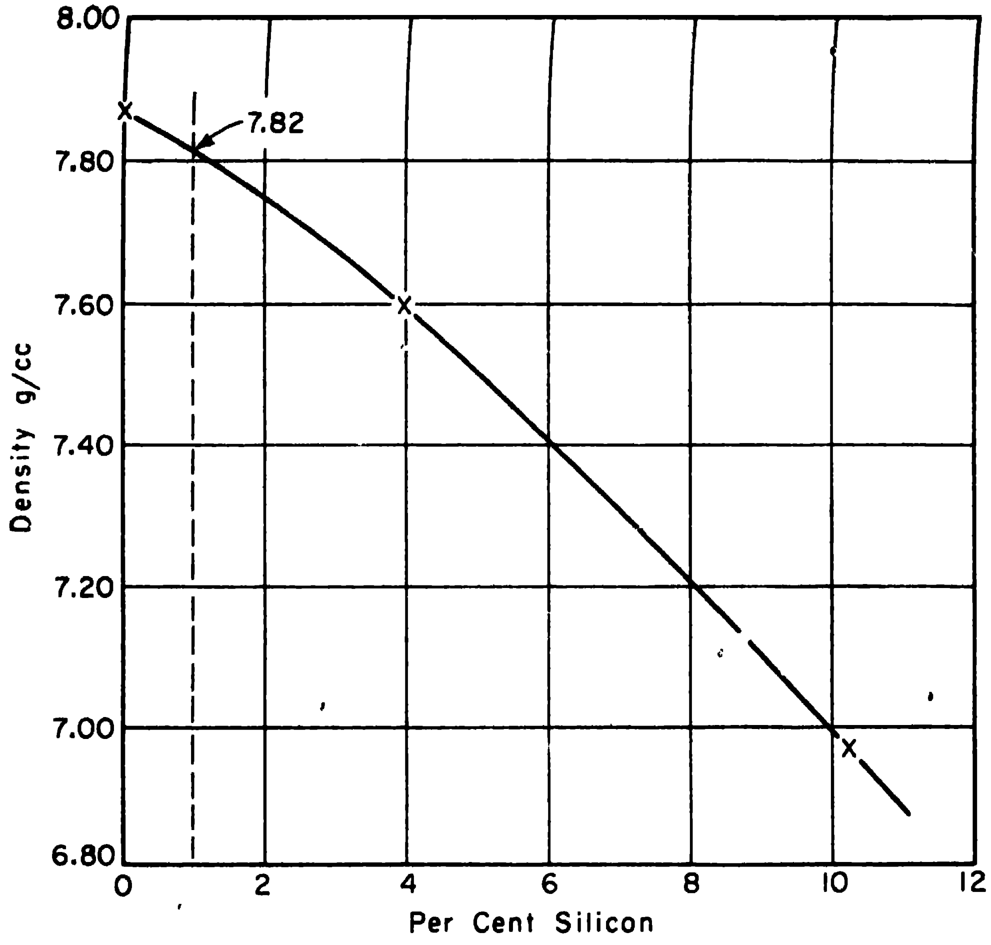


Fig. 1. **Effect of silicon on the density of iron-carbon alloys.**

The influence of silicon on the density of iron-carbon alloys, as shown in Fig. 1, which is based on the data above, is such that an iron containing 1 per cent silicon may be expected to have a density of approximately 7.82. With this information and the value for pure graphite given in Table 1, points for the solid curve in Fig. 2 can be calculated, showing predicted approximate densities for standard malleable irons whose carbon content ranges between 2.00 and 2.60 per cent in completely annealed metal. For this handbook,[65] values found in practice were checked against these calculated values, data being assembled from the literature and from standard 5/8-inch diameter cast test bars supplied by three producers in the following categories:

Producer I: Two white irons A and B of very similar chemical analysis together with a completely annealed ferritic malleable from iron A and an alloy-arrested-anneal pearlitic malleable from iron B.

Producer II: Arrested-anneal pearlitic malleable from four different heats.

Producer III: Completely annealed ferritic malleable iron from five different heats together with reheated and liquid-quenched pearlitic malleable produced from the same five heats, and in addition specimens *from two heats of reheated and liquid-quenched pearlitic malleable in* both machined and as-cast condition.

The chemical analysis of these groups of specimens is given in Table 2, together with data on other materials contained in the literature.[19]

TABLE 2. CHEMICAL COMPOSITION OF DENSITY TEST SPECIMENS

	Heat Designation	*C* %	*Mn* %	*Si* %	*P* %	*S* %	*Cr* %
Producer I	A	2.16	.38	1.17	.137	.095	.017
	B	2.27	.89	1.15	.135	.098	.019
Producer II	2D3-6-25	2.48	.47	1.35	.069	.245	
	2D8-12-15	2.42	.46	1.24	.084	.190	
	2D6-7-7	2.42	.44	1.46	.039	.167	
	2D2-7-6	2.39	.47	1.51	.058	.172	
Producer III	6-15-1-1	2.34	.24	1.09			
	6-15-5-2	2.28	.31	1.06			
	6-15-6-1	2.28	.30	1.11	.166	.073	
	6-15-7-1	2.39	.24	1.08	.162	.074	
	5-18-6-2	2.33	.26	.98	.166	.076	
	5-18-7-1	2.21	.33	1.08			
	5-18-7-1	2.26	.30	1.08	.162	.074	
Schwartz and Junge	No. 17	2.59	.39	1.06			
	No. 18	2.53					
	No. 23	2.53	.35	.91			
	No. 31	2.61					

To obtain density measurements, samples approximately ½-inch in length, cut from the test bars, were weighed in air and in water on an analytical test balance. The sample was suspended on a fine wire for weighing in water; because of the damping effect of the water, these values are reported only to 1 milligram (.001 gm.) accuracy. In all computations the density of water at the temperature of measurements was employed; the density of water equals 1 gram per cubic centimeter at approximately 4 degrees C. only, and is less at the temperatures at which measurements were made. Five samples were weighed from each group to secure a reasonable estimate of the density and a measure of the uncertainty in the results. The experimental values obtained are summarized in Table 3, as are data from the literature.[19] Each experimental density is the average of five determinations and is accompanied by stated 99 per cent confidence limits. Figure 2, showing the data in graphical form, affords a good comparison with the calculated densities mentioned earlier.

Completely annealed ferritic malleable iron, as Table 3 indicates, may be expected to have a density of approximately 7.35 ± 0.10, decreasing somewhat with increasing carbon content. Pearlitic malleable iron

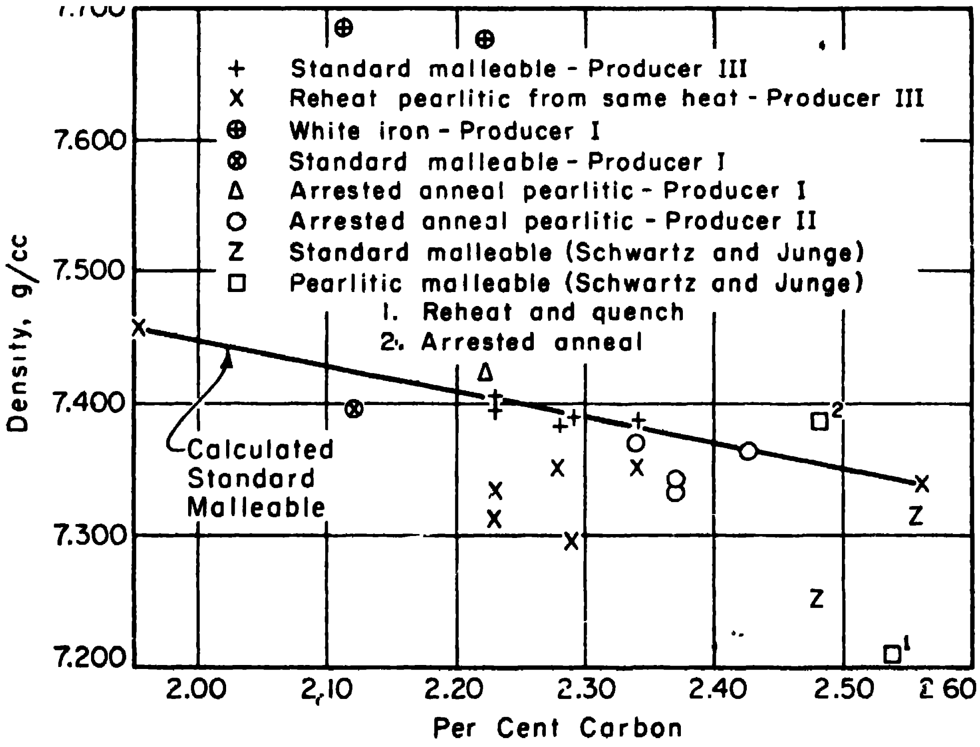


Fig. 2. **Effect of carbon content on the density of malleable iron. The solid line represents density values calculated at 1.0 per cent silicon = 7.82 g/cc.**

TABLE 3. DENSITY VALUES OF MALLEABLE IRON TEST SPECIMENS

(g/cc)

	Producer I	*Producer II*	*Producer III*	*Schwartz and Junge*[19]
White	A 7.684±.014			
Iron	B 7.679±.027			
Standard	7.396–.008		7.388±.015 (6-15-1-1)	7.2521 No. 23
Malleable	From		7.407±.018 (6-15-5-2)	7.3162 No. 31
	White		7.393±.016 (6-15-5-1)	
	Iron A		7.388±.024 (6-15-7-1)	
			7.383±.007 (6-15-8-1)	
Pearlitic	7.42±.011	7.368±.066 (2D3-6-25)	7.296±.021 (6-16-1-1)	7.2104‡ No. 17
Malleable	From	7.342±.131 (2D8-2-15)	7.332±.017 (6-15-5-2)	7.3916§ No. 18
	White	7.333±.098 (2D6-7-7)	7.313±.009 (6-15-6-1)	
	Iron B	7.374±.073 (2D2-7-6)	7.352±.023 (6-15-6-1)	
			7.350±.018 (6-15-8-1)	
			* 7.281±.010 (5-18-6-2)	
			† 7.280±.018 (5-18-6-2)	
			* 7.284±.010 (5-18-7-1)	
			† 7.293±.012 (5-18-7-1)	

*** Machined.**
† Not machined—unmarked values not machined.
‡ Reheat and quench.
§ Arrested anneal.

formed by the reheat and liquid-quench methods shows a somewhat lower density, between 7.20 and 7.35. Arrested-anneal pearlitic malleable irons, however, have a somewhat higher density, 7.33 to 7.42.

Good agreement is shown between the density (approximately 7.68) of the white iron specimens in Table 3 and the values for pearlite and iron carbide shown in Table 1. The fact that the experimental values for completely annealed ferritic malleable are somewhat lower than the calculated ones may result from a variety of causes such as uncertainty of the literature values for graphite and iron (ferrite) and the very probable creation of voids in the experimental samples by the diffusion of carbon to form nodules or aggregates.

The density of pearlitic malleable iron appears to depend on the method of manufacture. Pearlitic malleable produced by reheating and liquid-quenching completely annealed ferritic malleable (Producer 3) gave lower density than that of the original ferritic material. This fact can possibly be explained by reasoning that the complete graphitization of the ferritic malleable during annealing produces voids in the structure through the diffusion of the original carbon, that reheating causes solution of some of the graphite, and that formation of martensite or pearlite follows on cooling, but that the voids originally containing the graphite nodules are apparently not reduced in size during this process, and the volume of expansion accompanying the transformation lowers the density of the matrix. In pearlitic malleable iron made by the arrested-anneal process, on the other hand, graphitization is not permitted to go to completion, voids sufficient to contain the total carbon in the form of graphite hence are never found, and thus a somewhat higher density than that of the completely annealed material of similar analysis may result. Table 3 also presents a comparison between samples (Producer 3) measured as cast as well as some taken from the same test bar after the decarburized surface had been removed by machining, the effect of removing the decarburized rim being negligible in the case of the samples studied.

Specific Gravity

The specific gravity of a body is the ratio of its density to that of some standard substance, usually water at 4 degrees C. (39 degrees F.). It can be converted to a measure of mass through multiplication by the value for the density of water. If the metric system is employed, density and specific gravity are practically identical, since the density of water in that system is very nearly unity. To convert from the metric to the British system, the specific gravity of a substance must be multiplied by 62.4, the weight of a cubic foot of water in pounds.[20] Multiplication by 0.0361, the weight of a cubic inch of water, gives the weight per cubic inch of the substance being measured. The specific gravity of standard malleable iron at room temperature lies between 7.25 and 7.45, depending upon *composition. A comparison of the specific gravity of malleable iron with that of other materials is shown in Table 4.*

TABLE 4. SPECIFIC GRAVITY OF SOME COMMON MATERIALS[17,24]

	Specific Gravity	*Weight per Cubic inch (pounds)*	*Weight per Cubic foot (pounds)*
Water	1	0.0361	62.4
Gray Iron	6.95-7.35	0.251-0.265	433.6-458.6
Malleable Iron (standard and pearlitic)	7.20-7.45	0.261-0.269	449.2-464.6
White Iron (before malleablization) ...	7.67-7.75	0.276-0.280	478.0-484.5
Steel (cast, .06-1.22% carbon)	7.83-7.87	0.283-0.284	488.5-491.0
Magnesium (cast)	1.71-1.84	0.063-0.066	106.7-114.8
Aluminum (cast)	2.53-2.95	0.091-0.107	157.8-184.0
Titanium (pure)	4.45	0.164	285.2
Brass, 70-30 (wrought)	8.53	0.308	532.2
Copper (pure)	8.96	0.324	559.1

VOLUME

The specific volume of a substance is the amount of space occupied per unit mass and is usually expressed in cubic centimeters per gram. It is the reciprocal of the density. For pure iron at 68 degrees F., specific volume is 0.1271 cubic centimeter per gram.[17] Additions of carbon and silicon, which are lighter than iron, increase the specific volume. Malleable iron at 68 degrees F. has a specific volume between 0.134 ± 0.002 and 0.138 ± 0.002 cubic centimeters per gram.

CONTRACTION ON SOLIDIFICATION

Specific volume falls with decreasing temperature, since the metal becomes more dense as it gets colder. Iron castings at room temperature take up less space than the same weight of metal in the molten condition at, say, 2600 degrees F. During solidification, an especially marked contraction occurs; this is "solidification contraction." Still further contraction takes place during cooling from the temperature at which solidification is complete down to room temperature; this is "solid contraction."

Experience has shown that all white irons have about the same linear shrinkage—approximately one-quarter inch per foot—in cooling to room temperature.[5]

EXPANSION DURING ANNEAL

Offsetting part of this contraction is the permanent expansion which results from the malleablization treatment. This is not a thermal expansion due to the high temperature of the malleablizing process, but rather is a permanent increase in specific volume caused by changes which take place in the iron during heat-treatment. Ferrite and temper carbon, the structural components of malleable iron produced by the anneal, are more bulky than the iron carbide in white iron. Because of the growth during the heat-treatment, malleable iron regains part of the volume which the molten white iron lost on solidifying.[1,21] The amount of expansion is largely dependent on the percentage of carbon present in the iron. The higher the carbon content, the more temper carbon is formed, and the greater is the increase in volume. Experience has shown this expansion linearly to be approximately one-eighth inch per foot for castings of typical carbon contents.

Pattern Shrinkage Allowance

The net contraction for which allowance must be made in pattern design is the contraction which occurs when the castings solidify and cool to room temperature, less the expansion which takes place as a consequence of the malleablization treatment. The net allowance hence is a linear shrinkage of one-quarter inch per foot, minus one-eighth inch, or ⅛-inch per foot, about 1 per cent. This value will vary somewhat, depending on the composition of the melt and the shape of the casting.

Casting Stresses and Strains

When any metal freezes in a mold, the solidification and solid contractions create stresses within the casting, particularly if it has been poorly designed or if the mold itself hinders free contraction.

If such internal forces become sufficiently great to exceed the yield point of the metal at some temperature during the cooling process, permanent distortions or "casting strains" will occur. In extreme cases, where the casting stresses are so concentrated on a given section that they are higher than the ultimate strength of the material, a tear or crack will result.

Proper casting design and good foundry practice can, to a large degree, minimize casting stresses. Furthermore, with malleable iron the heat-treatment, which converts the white iron casting into a malleable product, also fully relieves internal stresses. Thus, regardless of how great the locked-up stresses may be in the as-cast condition, they are completely eliminated by the malleablizing treatment.

THERMAL VALUES

Specific Heat

Specific heat is the quantity of heat required to raise the temperature of a unit mass of material one degree. It is expressed either as calories required to raise the temperature of one gram one degree Centigrade, or as the number of British thermal units required to raise the temperature of one pound of the substance one degree Fahrenheit.

Specific heat rises with increasing temperature, the range for malleable iron being about 0.11 calorie per gram per degree C. at room temperature to 0.165 calorie per gram per degree C. at 800 degrees F.[5] Direct determinations give the following values:[22]

TABLE 5. MEAN SPECIFIC HEAT OF MALLEABLE IRON

Temperature Range (Degrees Fahrenheit)	*Calories per Gram per Degree Centigrade or B.t.u. per Pound per Degree Fahrenheit*
70-210	0.122
70-390	0.125
70-570	0.128
70-750	0.133
70-930	0.139
70-1110	0.146
70-1300	0.159

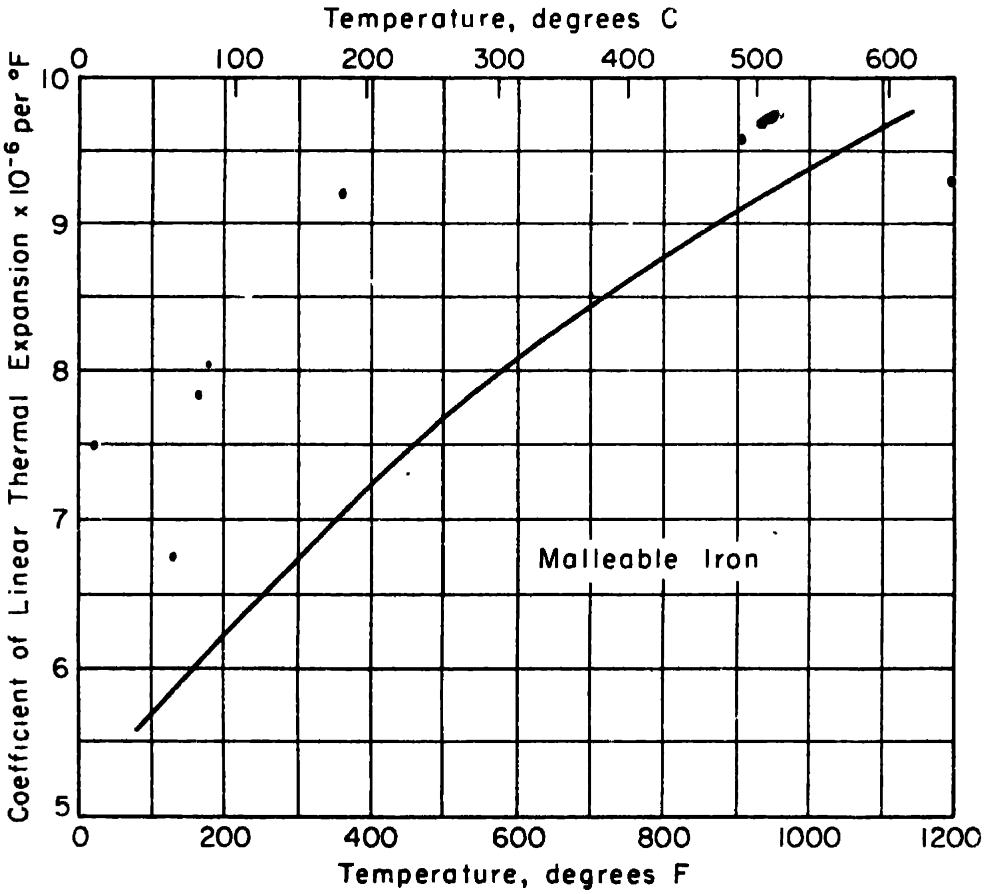


Fig. 3. Average coefficient of linear thermal expansion for malleable iron.

THERMAL EXPANSION

Most materials expand when they are heated and contract when they are cooled. In the designing of parts that are to be exposed in service to variations in temperature, these dimensional changes may be significant. If the part is to be permitted to expand and contract freely, adequate clearances must be incorporated in the over-all design. On the other hand, if the part is rigidly held and is not allowed to change dimensionally with differences in temperature, such constraint sets up stresses within the material which must be considered in the selection and design of the part.

The expansion or contraction in isotropic substances, such as malleable iron, is the same in all dimensions, and so is usually measured in linear units. The rate at which this change occurs with temperature variations is expressed by a number called the *coefficient of linear thermal expansion*. The average coefficient number (c) between two temperatures (t_1 and t_2) may be computed from the formula

$$c = \frac{L_2 - L_1}{(t_2 - t_1) L_0},$$

where L_1 and L_2 represent the lengths of the specimen at each of the two temperatures, t_1 and t_2 respectively, and where L_0 is the initial length (usually at room temperature or at zero degrees).

Since malleable iron, like most materials, changes dimensionally at a more rapid rate at higher temperatures, the coefficient of linear thermal expansion is greater at higher temperatures, rising from a mean of 5.9×10^{-6} per degree F. (10.6×10^{-6} per degree C.) between 68 degrees F. and 212 degrees F. (20 degrees C. and 100 degrees C.) to 9.5×10^{-6} per degree F. (17.1×10^{-6} per degrees C.) between 1000 degrees F. and 1100 degrees F. (538 degrees C. and 593 degrees C.). The average coefficient of linear expansion for malleable iron between any two temperatures may be obtained from the graph, Fig. 3. To determine how much a casting will change dimensionally if the temperature is varied, the length, temperature difference, and coefficient of thermal expansion are multiplied together; that is, $L_1 \times (t_2 - t_1) \times c$.

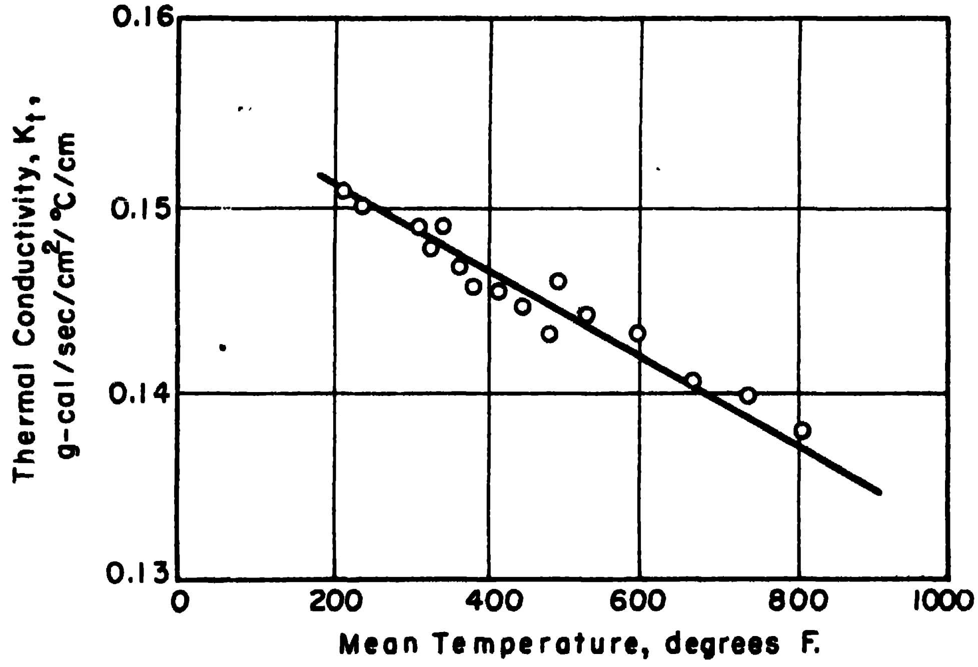


Fig. 4. Thermal conductivity (K_t) of malleable iron.

Thermal Conductivity

Thermal conductivity is the measure, in gram-calories per second per *square centimeter per degree Centigrade per centimeter*, of the ability of a substance to transfer heat. The thermal conductivity of malleable iron decreases with rising temperature, from 0.122 at 80 degrees F., to .095 at 700 degrees F.[5]

Standard malleable iron values range from 0.151 for a mean temperature of 212 degrees F. to 0.138 for a mean temperature of 800 degrees F. These data are summarized in Table 6,[28] and are charted in Fig. 4.

Table 6. Thermal Conductivity of Malleable Iron

Temperature Range (Degrees Fahrenheit)	*Mean Temperature (Degrees Fahrenheit)*	*Thermal Conductivity* (K_t)*
153-273	212	0.151
163-307	235	0.150
215-400	307	0.149
225-422	324	0.148
273-395	334	0.149
250-476	363	0.147
307-453	380	0.146
278-538	408	0.146
395-585	440	0.145
322-612	482	0.143
400-586	492	0.146
422-628	524	0.144
476-710	594	0.143
538-800	669	0.141
585-883	734	0.140
642-972	807	0.138

* In gram-calories per second per square centimeter per degree Centigrade per centimeter.

ELECTRICAL PROPERTIES

Resistivity

Resistivity or specific resistance, "R," (reciprocal of conductivity) is defined as the resistance, measured between two faces, of a volume of material of unit cross section and unit length at a specified temperature. As a consequence of this definition, units of resistivity have the dimensions of resistance times length, and values are normally ohm-centimeters or microhm-centimeters, the latter being a more convenient unit for calculations.

Resistivities of ferrous materials range from a value of 10 microhm-cm. for very pure iron to approximately 30 microhm-cm. for carbon and alloy steels and values as high as 84 microhm-cm. for high alloy steels, all at 20 degrees C.[17,24,25,26]

Both resistivity and its variation with temperature are very sensitive to the presence of impurities in the metal. The effect depends upon whether the impurity is present in the form of microconstituents, as for instance combined carbon, or enters into the lattice structure so as to affect the lattice constants, as in the case of silicon.

For this reason a distinction must be made between standard and pearlitic malleable irons. Resistivity of the former should be relatively unaffected by the amount of carbon present in the nodular form, but should be quite sensitive to the presence of other alloying elements and impurities. Measurements reported by Schwartz[19] in 1941 on standard malleable iron of 2.50 to 2.64 per cent carbon, 0.9 to 1.05 per cent silicon, and 0.35 to 0.39 per cent manganese give resistivity values from 27 to 34 microhm-cm.

Table 7 presents typical electrical values of a number of metals for comparison.

TABLE 7. ELECTRICAL PROPERTIES OF SOME METALS [17,18,21,23]

Material	*Resistivity* (*microhm-cm. at 20° C.*)	*Conductivity* (*microhm*$^{-1}$-*cm*$^{-1}$)	*IACS** (%)
Silver (pure)	1.59	0.629	105
Copper (pure)	1.673	0.598	100
Aluminum (pure)	2.655	0.377	63
Iron (pure)	9.71	0.103	17
Carbon steel (.07-1.5% C)	13-20	0.077-0.050	8-11
Low Alloy Steel	20-43	0.050-0.023	4-8
Standard Malleable Iron	27-34	0.037-0.029	5-6
Pearlitic Malleable Iron	37-41	0.027-0.024	4-5
High Alloy Steel	42-84	0.024-0.012	2-4
Gray Cast Iron	100	0.010	2

*** International annealed copper standard.**

EFFECT OF TEMPERATURE ON RESISTIVITY

Electrical resistivity increases with temperature. Modern theories of metals[27,28,29] predict that in the ideal case resistivity should be proportional to absolute temperature. Observations[17,24,25] are in approximate agreement with this over moderate temperature ranges of 100 to 200 degrees F. As noted above, actual values of resistivity at given temperatures will be determined by chemical composition and the particular relationship of the alloying element or impurity to the structure of the metal at that temperature. In the case of malleable irons, carbon begins to be redissolved at about 1350 degrees F., producing some increase in the resistivity of the metal. Above this temperature most ferrous materials also become austenitic (face-centered cubic lattice) in structure. Values of resistivity lie in a narrow range, which becomes increasingly small with rise in temperature. Typical values at 2300 degrees F. range from 124 to 130 microhm-cm. Malleable iron appears typical in the latter respect.

Figure 5 gives a graphical comparison of the electrical resistivity of malleable iron and a number of representative steels. The curve in Fig. 6 shows the variation of resistivity with temperature for malleable iron.[22].

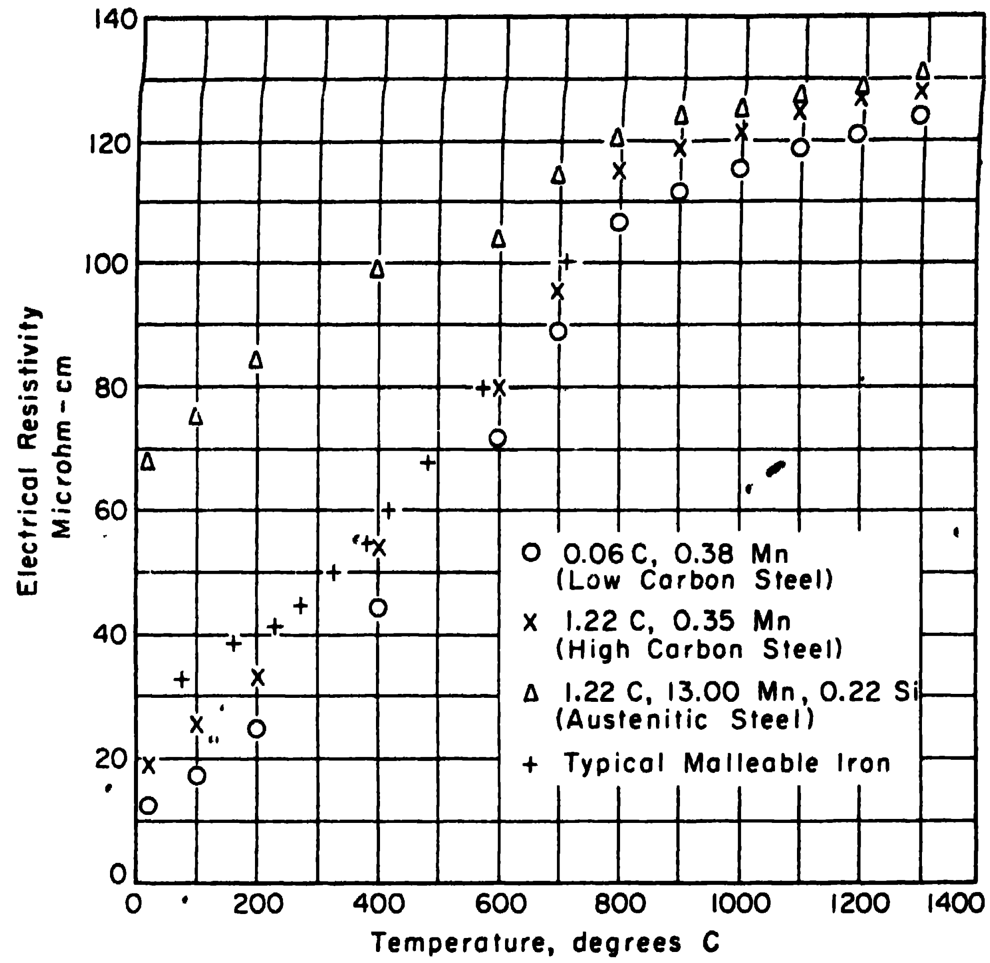


Fig. 5. **Comparison of electrical resistivity of malleable iron with three representative steels at different temperatures.**

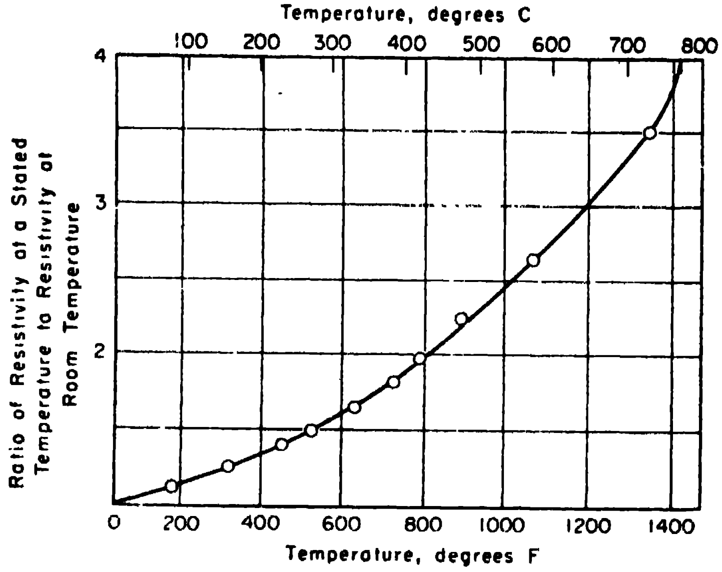


Fig. 6. **Relationship of the electrical resistivity of malleable iron at elevated temperatures to that at room temperature.**

CONDUCTIVITY

The electrical conductivity of a metal is the reciprocal of its resistivity. Conductivity values have been computed from the resistivities of several metals and are expressed in Table 7 in both microhm^{-1}-centimeters^{-1} and percentages of the conductivity of pure *annealed copper*.

MAGNETIC PROPERTIES

When a magnetizing force is imposed on it, a ferromagnetic material becomes magnetized. In the mks system, the applied magnetizing force ("H") is measured in oersteds (which are equal to 1.257 x ampere turns per centimeter); the degree to which the material is magnetized ("B") is called the magnetic flux density or *inductance* and is expressed in gausses (the number of lines of force per square centimeter). When the magnetizing force H is varied, in ferromagnetic materials, the induced magnetism B functions in a non-linear relationship to H. The ratio of B to

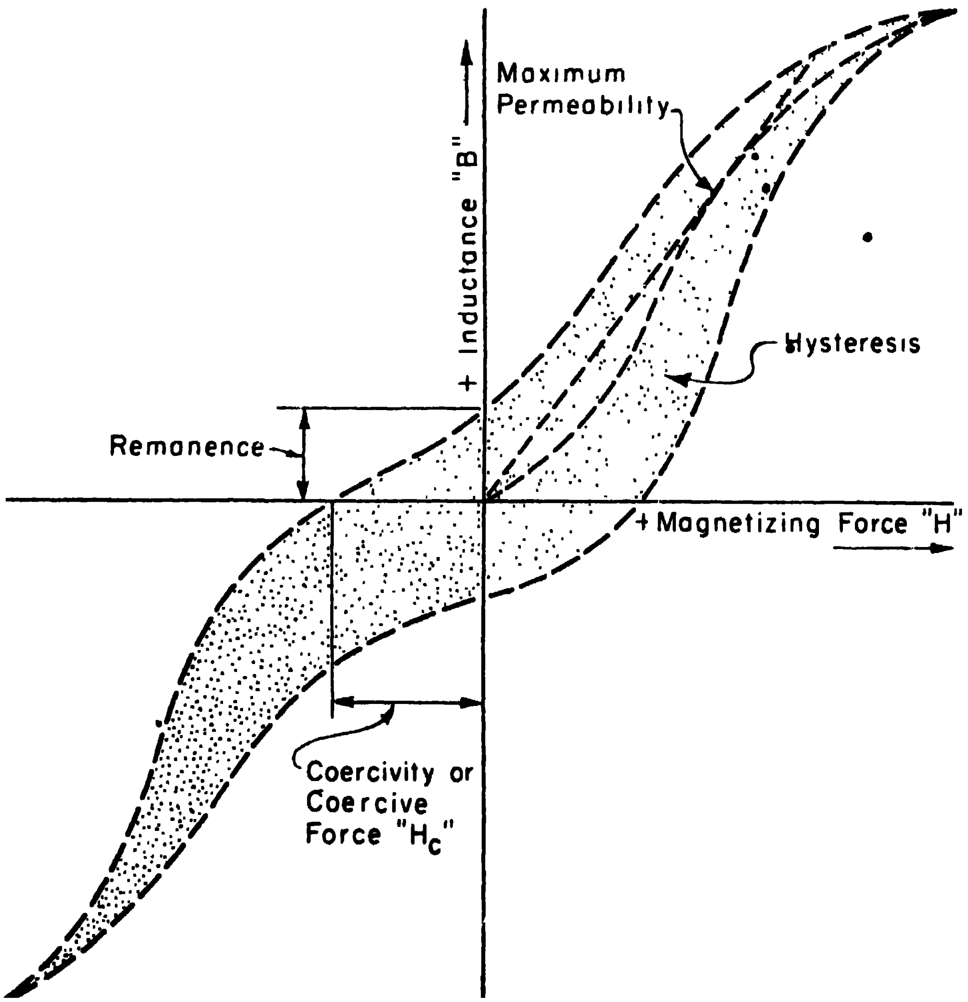


Fig. 7. **Magnetization diagram showing the relationships among the magnetizing force *H*, inductance *B*, remanence, and coercivity.**

H (i.e. gausses/oersteds) is known as the magnetic *permeability* of the material. The maximum permeability may be found graphically by drawing a line tangent to the knee of a magnetization curve and through its origin, as is illustrated in Fig. 7. The maximum permeability of malleable iron is about 2350, and occurs at about 2 oersteds (approximately 4 ampere turns per inch).[30]

If the magnetizing force is removed after having been at a relatively high initial value, some induced magnetism remains in the ferromagnetic material. This is called *remanence*. To eliminate it, a negative magnetiz-

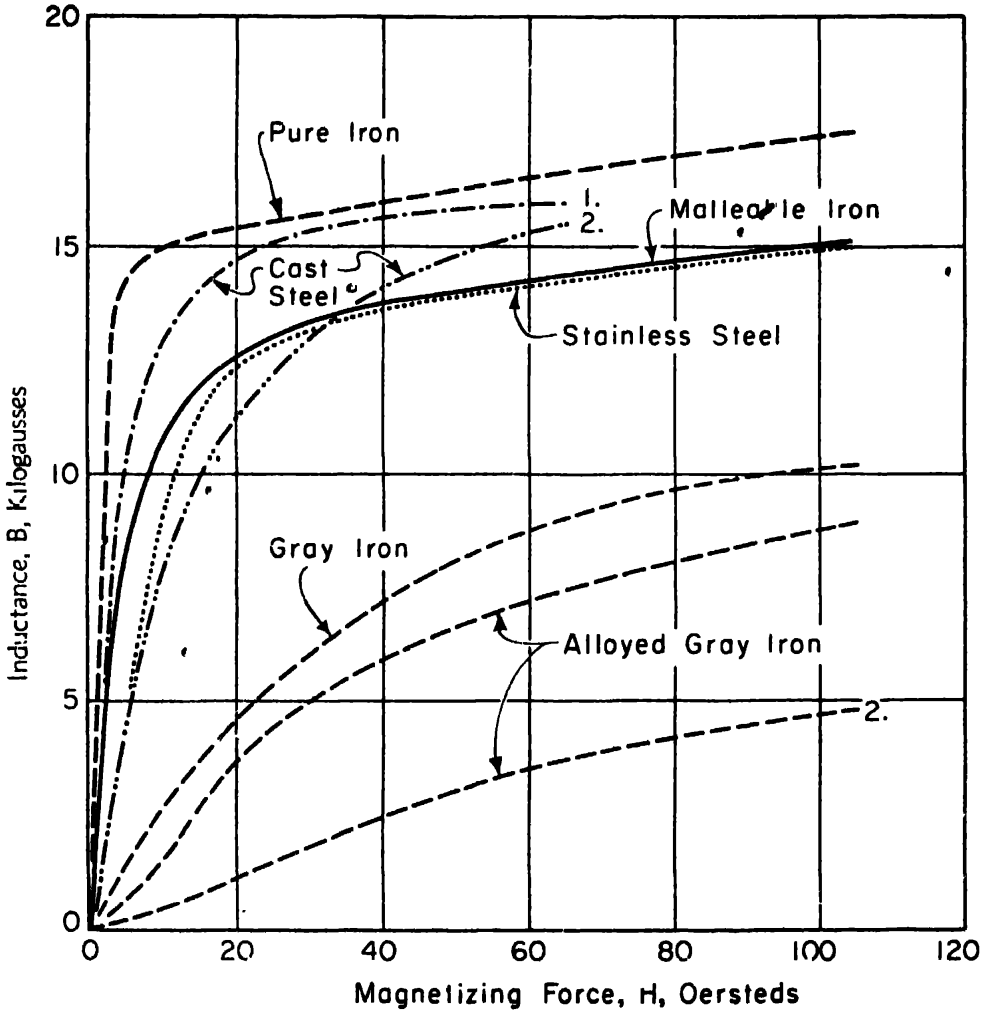


Fig. 8. Standard magnetization curves for a number of ferrous alloys. Compositions were as follows:

Alloy	*Total Carbon* %	*Silicon* %	*Manganese* %	*Sulfur* %	*Chromium* %	*Nickel* %
Malleable	2.24	0.89	...	....	....	...
Cast Steel #1	0.08	0.08	0.05	0.055	....	...
Cast Steel #2	0.27	0.25	0.82	0.058	....	...
Stainless Steel	0.10	...	0.42	....	12.42	0.31
Gray Iron	3.06	2.54	...	....	....	...
Gray Iron Alloyed #1	3.66	0.32	...	....	....	0.71
Gray Iron Alloyed #2	3.52	0.23	...	....	....	5.40

ing force (i.e., the *coercive force,* "H_c") must be applied. When a ferromagnetic material is put through a complete cycle of magnetization, demagnetization, and remagnetization, and is finally returned to its original magnetic state, heat is generated within the material. This is called *hysteresis* and is proportional to the area enclosed by a complete magnetization loop.

Pure iron, having no elements in solution and containing no inclusions, exhibits excellent magnetic properties (that is, high maximum permeability and saturation, and negligible coercivity and hysteresis). However, if even a small quantity of carbon or other element is dissolved in the ferrite, these properties become markedly reduced. Further harmful results arise from the presence of non-magnetic inclusions, which may be in the form of combined carbon, free graphite, sulfides, oxides, and so on. The degree to which such inclusions will impair the magnetic properties of an iron depends on the amount and disposition of them. Large flakes of graphite, as are found in gray cast iron, so disrupt the continuity of the ferrite that the magnetic properties are drastically lowered. Finely dispersed combined carbon, such as tempered martensite, likewise exerts a harmful effect. Combined carbon in the form of laminar pearlite is less detrimental; coarse spheroidite is injurious to a still lesser degree.

While malleable iron contains free graphite in its matrix, the graphite is lower in quantity than that found in gray irons and, being compacted into temper carbon nodules, it imposes less discontinuity on the matrix. The magnetic properties of standard malleable iron are further enhanced by the fact that the annealing treatment, which is an inherent part of malleable manufacture, completely eliminates combined carbon from the structure. Both hysteresis loss and coercivity hence are relatively low. Standard B-H magnetization curves for a number of ferrous alloys are shown in Fig. 8. It is apparent from this illustration that malleable iron possesses magnetic characteristics similar to those of the ferritic (12 per cent Cr.) stainless steels and approaches those of mild carbon steels over this range of magnetization.

TABLE 8. COMPARATIVE MAGNETIC PROPERTIES[18,32,34]

Material	*Coercivity, oersteds*	*Maximum Permeability*	*B, at H-100 gausses*	*Hysteresis ergs/cc/cycle*
Electrolytic Iron	0.36	14,400	17,700	0
Cast Steel (.2% C.)				
As-cast	1.51	....	.....	.....
Annealed	0.37	3,500	.....	3,500
Malleable Iron	2.38	2,140	15,200	6,900
12% Cr. Steel	3.6	1,000	15,100	.....
Gray Cast Iron				
As-cast	12.7	230	10,300	32,435
Annealed	4.6	680	.....	12,360
Hardened Steel	52.4	110	.....	.....

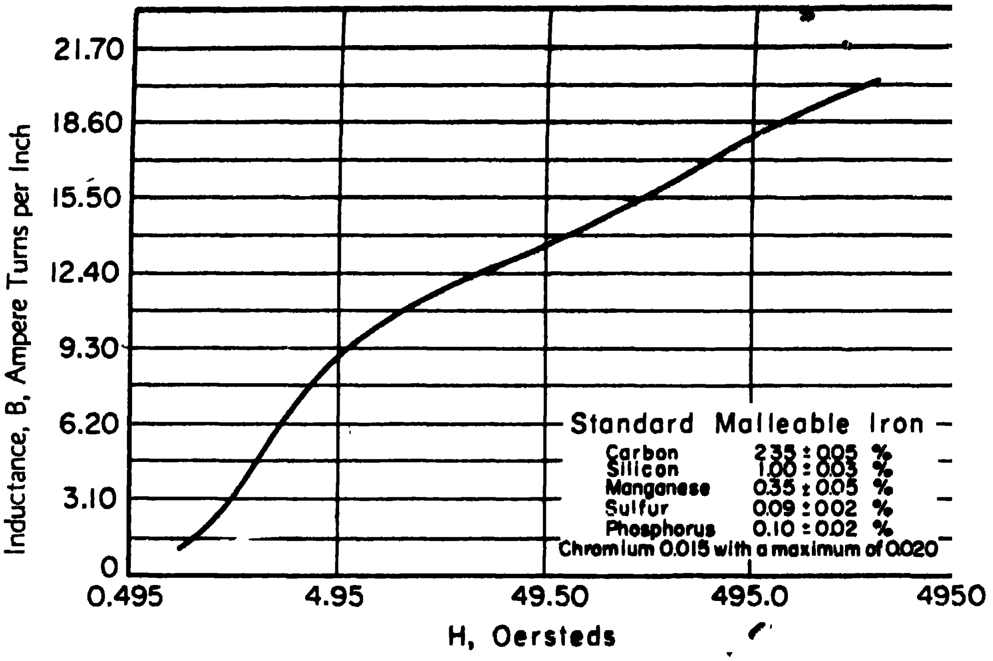


Fig. 9. **Magnetization curve for standard malleable iron.**

A comparison of the magnetic properties of malleable iron with those of some other materials is given in Table 8. For a group of ten different malleable irons, tested in a Clayton type coercimeter, a mean coercivity value of 2.89 oersteds was obtained.[19] Fig. 9 shows a standard magnetization curve for ferritic malleable iron.

CURIE POINT

The Curie point is defined as the temperature at which ferromagnetic properties disappear and all ferromagnetic substances become merely paramagnetic. This occurrence is important in relation to some processing. Often induction heating is employed for heat-treatment or hardening of a part. At the Curie point a sudden change occurs in loading of the induction machine, because of the fact that heat losses in the workpiece above this temperature can be caused only by eddy currents. Thus resistivity becomes the determining factor (see the section on resistivity page 66). Often automatic controllers must be employed to adjust and stabilize the load on induction machines.

Transition actually takes place over a range of temperatures because of the gradual decrease in saturation magnetization,[27,31] which occurs with increasing temperature. The upper limit of the saturation value at any temperature is determined by the number of electrons in the outer d-shell of the atom available to align their spin axes with the magnetic field. At low temperatures practically all of the electron spins are locked in alignment if the field is high; thus magnetic saturation results. As temperature increases there is a tendency for more and more of these electrons to reverse their spin axes, eventually achieving a completely random distribution, which is associated thermodynamically with a lower free energy and a consequent gain in entropy of the atoms in the material. This is the Curie point.

Loss of ferromagnetism is variously reported to begin in pure iron at 1415 to 1436 degrees F. and to continue to 1456 to 1472 degrees F.[32] Carbon content has relatively little effect on the Curie range in material such as the matrix of standard malleable or pearlitic malleable iron containing no massive carbides.[17] The effect of silicon, however, is quite large, as is evident in Fig. 10.[17] The Curie point is reduced almost linearly from 1436 to 914 degrees F. by the addition of silicon. Stanley reports a Curie point for iron carbide (cementite) at 392 degrees F., so that pearlitic malleable iron might reflect this change.[32] Unpublished at the time of writing, a study of a malleable iron containing 2.11 per cent carbon, 1.40 per cent silicon, 0.35 per cent manganese, 0.077 per cent sulfur, and 0.153 per cent phosphorus showed the Curie transformation at 1455 ± 20 degrees F. This lies in the range reported by the authorities cited above, but is somewhat higher than might be expected in view of the silicon content.

The Curie point has sometimes been confused with the alpha to gamma phase transformation, which for many ferrous alloys occurs in the same temperature range. X-ray diffraction studies[32] make it possible to identify the separate phenomena.

In the unpublished study mentioned above, it was possible to observe both effects, the phase change taking place at 1313 degrees F. and the Curie transition being complete at 1455 degrees F.

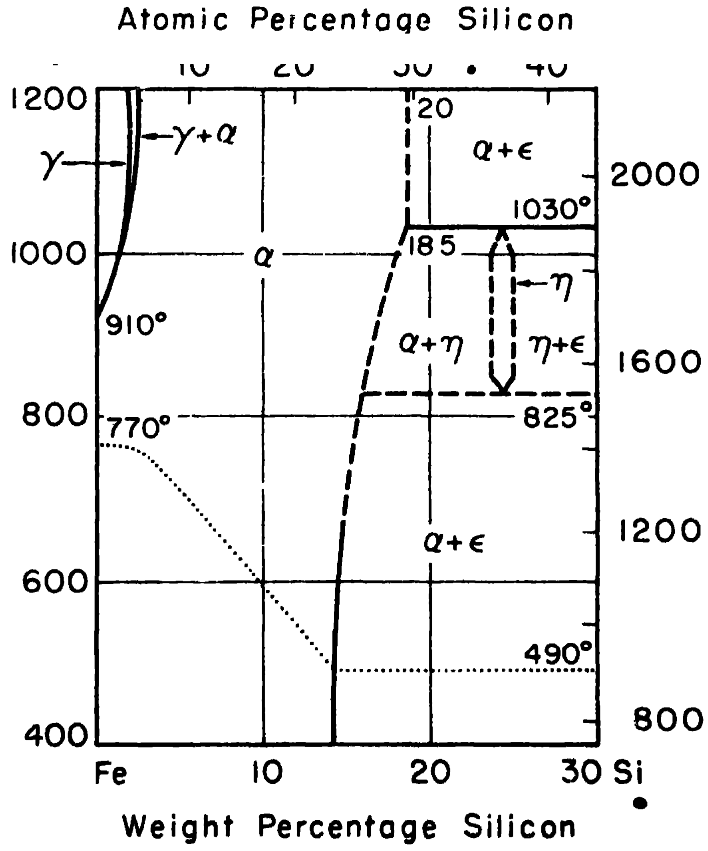


Fig. 10. **A section of the iron-silicon equilibrium diagram. The dotted line at the lower left shows the variation in the Curie point with increasing silicon.**

V

MECHANICAL AND ENGINEERING PROPERTIES OF STANDARD MALLEABLE IRON

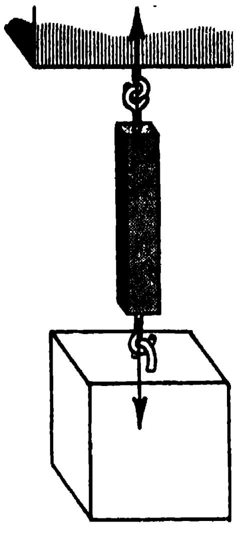
THE WIDE range of applications in which standard malleable iron is used demonstrates the recognized value of its combination of strength, ductility, ready machinability, and shock resistance as well as other desirable engineering characteristics. It is adopted by design engineers for many uses because of its mechanical and engineering properties, which will be discussed in this chapter. The principal specifications to which it is made are given in Table 2 of Chapter III, page 52.

MECHANICAL PROPERTIES

Since the mechanical properties of a metal—those involved in its behavior under stress—indicate the service that can reasonably be expected from a part made of it, they are of decided importance to both designer and user. The following are considered to be of major significance: yield point, tensile strength, elongation or ductility, modulus of elasticity, hardness, fatigue strength, damping capacity, shear strength, torsional strength, compressive strength, and impact resistance. Standard tests with standard test specimens make possible the direct comparison of many of these properties, though for a few, present tests and test specimens can give only approximations.

The properties of most cast metals are influenced in varying degrees by the thickness of sections. Because of the uniformity and character of structure of malleable iron, variations of strength and other properties within a malleable casting having both light and heavy sections are at a minimum. Results derived from tests of separately cast specimen bars hence furnish a close appraisal of the properties of malleable castings made from the same metal as the bars.

PROPERTIES IN TENSION



Specimen Loaded in Tension

The tensile test, commonly used as one of the chief methods of judging the quality of a metal for service, consists of applying a slowly increasing load to a test specimen until it is pulled apart. The load thus applied is called "stress." "Unit stress" is the stress per unit area. As the stress is applied, it causes deformation in the specimen, ultimately culminating in fracture. Such deformation, called "strain" when measured along the stress axis, is commonly expressed either as unit deformation per linear unit of gage length of uniform section or as a percentage change over a specified gage length.

As its standard test specimen, the malleable castings industry uses the unmachined bar specified in the Standards of the American Society for Testing Materials. The standard bar, as shown in Fig. 1, is ⅝-inch in diameter over the central 2½ inches between the two grip ends, which are conventionally each 2½ inches in length and ¾-inch in diameter. It thus has an over-all length of 7½ inches, with sections varying from ⅝-inch to ¾-inch in diameter. The bar is gated and fed in a manner similar to that in which malleable castings are customarily gated and fed, as Fig. 2 shows. It is poured from the same metal and at the same time as the castings it represents, and is given the same malleablizing anneal, being suitably marked to insure identification. The malleable iron test bar is a typical malleable casting. It will be noted in Fig. 2 that a standard impact test wedge and a ¾-inch cube for chemical analysis are cast on the same gate with the test bar.

The enlarged ends for engagement with the testing machine heads may be formed in any desired manner; usual practice is shown in Fig. 1, standard V machine grips being employed. An alternative shorter bar with larger grip ends, shown in Fig. 3, is occasionally used with special

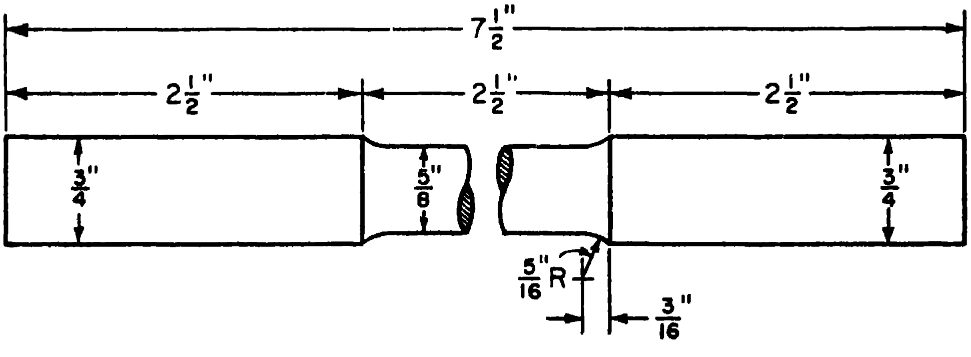


Fig. 1. **Design of tensile test specimen for malleable iron.**

Fig. 2. **A typical gating arrangement for casting standard tensile test bars, impact wedge, and chemical analysis cube.**

holders. Under A.S.T.M. requirements, the standard bars are tested with a machine head speed of not over ½-inch per minute up to the yield point and with a head speed of not over 2 inches per minute above the yield point. During the initial stages of a tensile test, deformation in the specimen is directly proportional to the load being applied. As the load continues to be increased, a strain is reached above which this linear relationship of stress to strain (*i.e.* Hooke's law) no longer holds. The stress at this point is known as the *proportional limit.*

If small stresses on a specimen are removed, the specimen will return to its original dimensions. However, if the magnitude of such stresses is progressively increased, a stress will eventually be reached which, after having been removed, will be found to have left some permanent distortion or strain in the specimen. The greatest stress which a material can

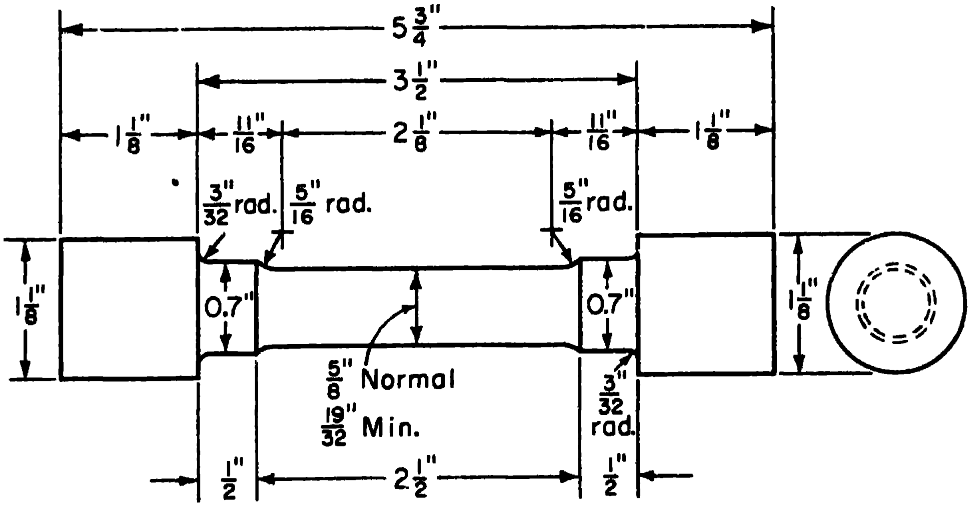


Fig. 3. **Alternate malleable iron tensile test specimen with large grip ends.**

develop without undergoing such permanent change in the original dimensions after the stress has been released is called the *elastic limit.* Because of the proximity of the values for both proportional and elastic limits, the terms are often used freely for each other.

YIELD POINT

At a stress somewhat above the proportional limit in standard malleable iron a marked increase in strain develops without the application of additional load. This is the yield point of the material. When this stress is reached in a tensile test, the pointer of a dial-indicating machine hesitates, the beam of a lever-type machine drops momentarily, or a dip appears in the autographic curve for the test. The yield point in tension of Grade 32510 malleable iron is 32,500 to 38,000 pounds per square inch; for Grade 35018 it is 35,000 to 40,000 pounds per square inch. Since for standard malleable iron the proportional limit and yield point lie so close together, the latter is the universally accepted term for indicating the approximate stress at or above which plastic yield might impair the usefulness of the material.

The term "yield strength" is sometimes loosely used as synonymous with "yield point," but this usage is not strictly correct. Yield strength is properly used only in relation to test values for materials which never show an arrest or "knee effect" in the stress-strain curve. For such materials, an arbitrary permanent deformation is set up to define the yield strength value. Generally it is specified as an increase of 0.5 per cent in the original gage length of the test specimen or is taken at 0.2 per cent offset on the stress-strain diagram. The two types of curves are shown in Fig. 4.

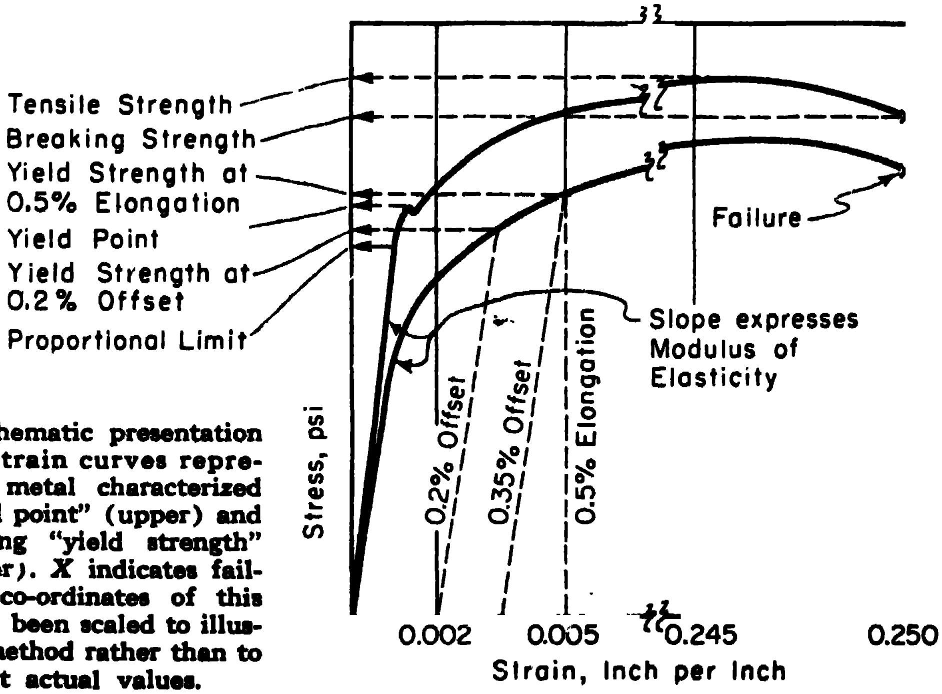


***Fig. 4.* Schematic presentation of stress-strain curves representing a metal characterized by a "yield point" (upper) and one showing "yield strength" only (lower). *X* indicates failure. The co-ordinates of this figure have been scaled to illustrate the method rather than to present actual values.**

A word of caution should be spoken with regard to these measurements. The apparent yield point as measured is a function of the strain rate, which in turn is a function of the particular machine being used to perform the test. For the testing of malleable iron the American Society for Testing Materials specifies that after a stress has been reached which is equivalent to approximately 50 per cent of the anticipated yield point value, the speed of the moving head of the testing machine is not to exceed ½-inch per minute up to the yield point. Testing at strain rates lower than 0.5-inch per minute may reduce the apparent yield point by as much as 5 per cent or more.[35,36] When proper care is exercised in testing, the yield point and the values of yield strength obtained by the 0.2 per cent offset method or by the 0.5 per cent total extension method agree very closely and may be regarded as very near the true value.

TENSILE STRENGTH

The tensile strength of a material is the maximum load carried by a specimen tested to failure in tension, expressed as stress per unit original cross-sectional area. In accordance with A.S.T.M. requirements for malleable iron, the testing machine head speed may be increased, after the yield point has been passed, up to 2 inches per minute. The tensile strength of Grade 32510 malleable is 50,000 to 58,000 p.s.i. and for Grade 35018 it is 53,000 to 60,000 p.s.i.

The yield point of standard malleable thus can be considered to be approximately 65 per cent of the tensile strength of the material. Most metal parts are so designed that they will not be deformed in service by anticipated structural loading. Therefore it is often of far more significance to consider the yield point than to think in terms of the tensile strength of a material. Certainly metal with a yield point of 35,000 p.s.i. can be used with greater confidence in highly stressed castings than can one with a higher tensile strength but with a yield point of only 30,000 p.s.i.

ELONGATION

The amount which the gage length of a tensile test bar has stretched, as measured after fracture, is the elongation. This is usually stated as per cent in two inches. Grade 32510 standard malleable iron has an elongation from 10 to 18 per cent; Grade 35018 has a range of 18 to 30 per cent.

When loaded in tension, ductile materials decrease in cross section as they approach the breaking point. The decrease is called "reduction of area" and is measured in per cent of the original area. Some metals show a marked decrease, known as "necking in," at the break point just before fracture occurs. The broken cast steel test bar (lower in Fig. 5) shows heavy necking in at the break point, in contrast to the malleable iron test bar above it. Malleable iron elongates throughout the entire gage length

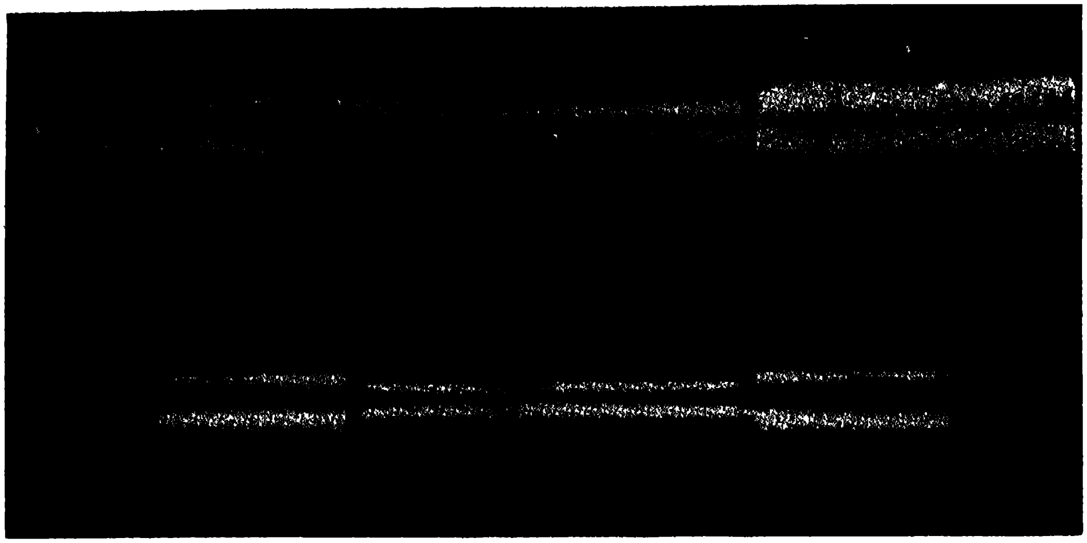


Fig. 5. **The cast steel test bar (lower specimen) shows heavy "necking" at the point of fracture. The necking in malleable iron is less pronounced indicating that malleable elongates throughout the entire gage length.**

and typically shows between 14 and 30 per cent reduction of area at the point of fracture. Since it indicates that stresses are spread over a greater area, this distribution of elongation is a favorable one.

Elongation is a measure of the ductility of malleable iron; it is shown in Fig. 6, where the test bar of Grade 35018 standard malleable iron can be seen to have elongated 25 per cent in the two-inch gage length. The

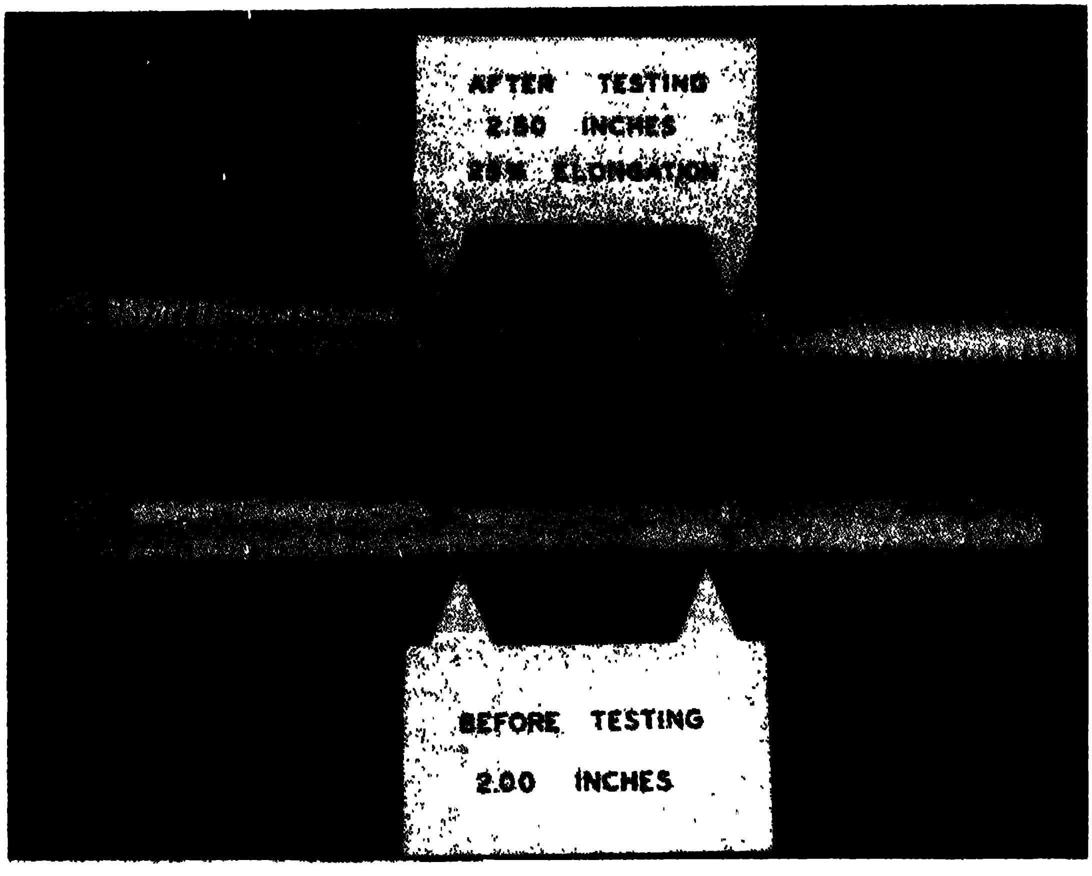


Fig. 6. **The excellent ductility of malleable iron is illustrated here. This grade 35018 test specimen elongated 25 per cent in a 2-inch gage length.**

ductility of standard malleable iron is also clearly indicated in Fig. 7, showing a standard tensile test bar of Grade 35018 standard malleable which has been bent cold to 180 degrees. Tensile strength of 54,350 p.s.i., yield point of 35,400 p.s.i., and elongation of 21 per cent in 2 inches were values given by a companion bar from the same heat. Similar excellent ductility is shown in Fig. 8, a standard bend test specimen of Grade 35018 standard malleable as used in British and Canadian practice, subjected to a full 180-degree cold bend without fracture A standard tensile test bar from the same heat showed tensile strength of 55,450 p.s.i.; yield point

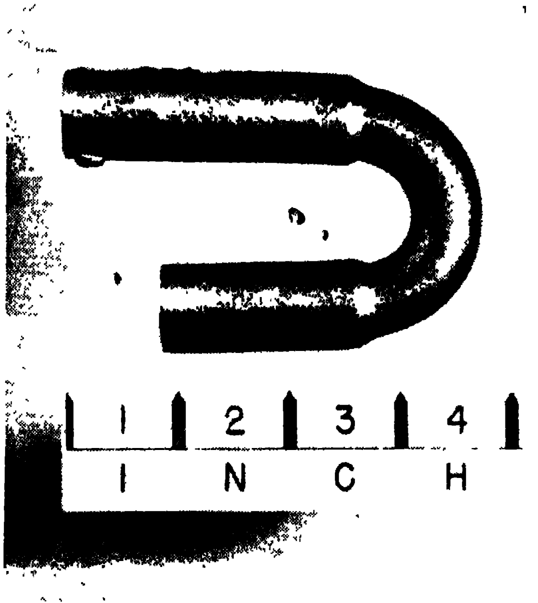


***Fig.** 7.* **This standard malleable iron test bar, Grade 35018, has been cold bent a full 180° without fracture.**

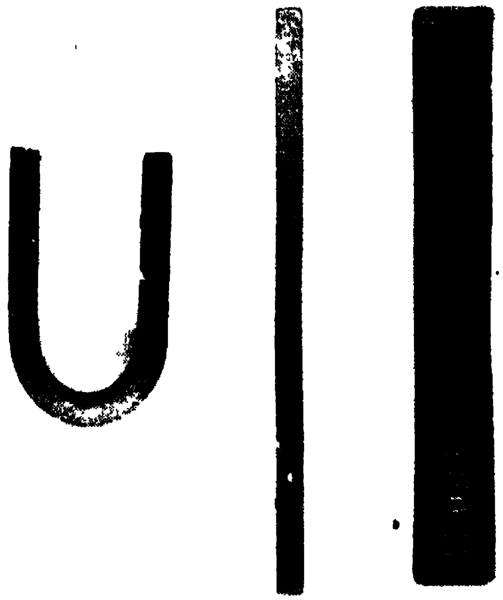


***Fig.** 8.* **The standard Canadian and British bend test bar of Grade 35018 malleable iron has been bent 180° without fracture.**

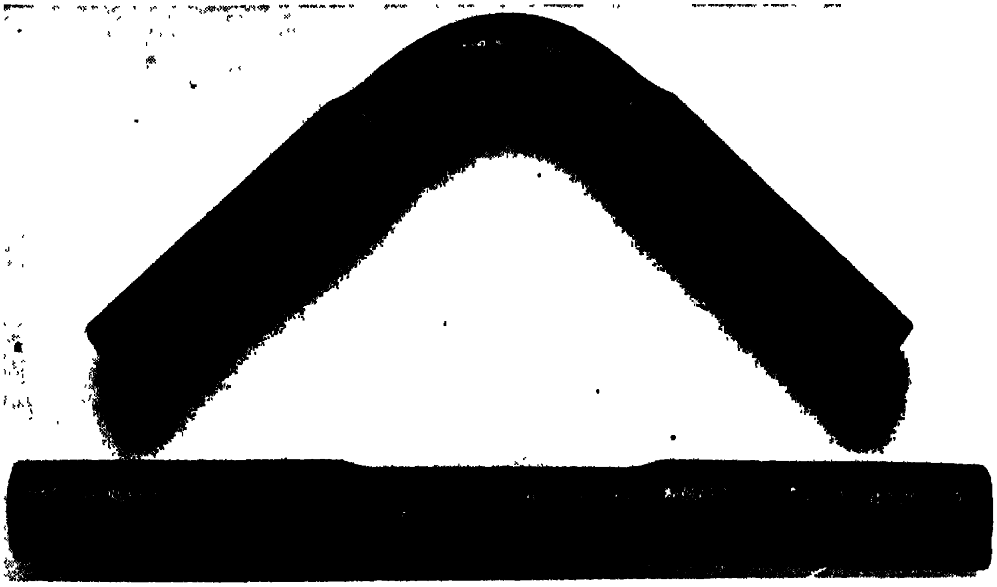


***Fig.** 9.* **Grade 32510 has good ductility as illustrated by cold bending this test bar 90° without fracture.**

35,000 p.s.i.; elongation 21 per cent in 2 inches. The ductility available in Grade 32510 standard malleable iron is shown in Fig. 9, where the standard tensile test bar has been cold-bent 90 degrees. Tensile values for a companion bar from the same heat were: tensile strength 53,000 p.s.i.; yield strength 36,000 p.s.i.; elongation 14 per cent in two inches.

TENSILE TEST VALUES

Representative tensile test values for standard malleable iron in its two grades are given in Table 1.

TABLE 1. TENSILE TEST VALUES

	Tensile Strength (p.s.i.)	*Yield Point (p.s.i.)*	*Elongation (per cent in 2")*
Grade 32510			
Minimum	50,000	32.500	10
Most probable value	52,000	34,000	12.5
Grade 35018			
Minimum	53,000	35,000	18.0
Most probable value	55,000	36,500	20.0

Tensile test results for 434 air furnace heats of Grade 32510 standard malleable iron are shown in the bar diagram, Fig. 10.

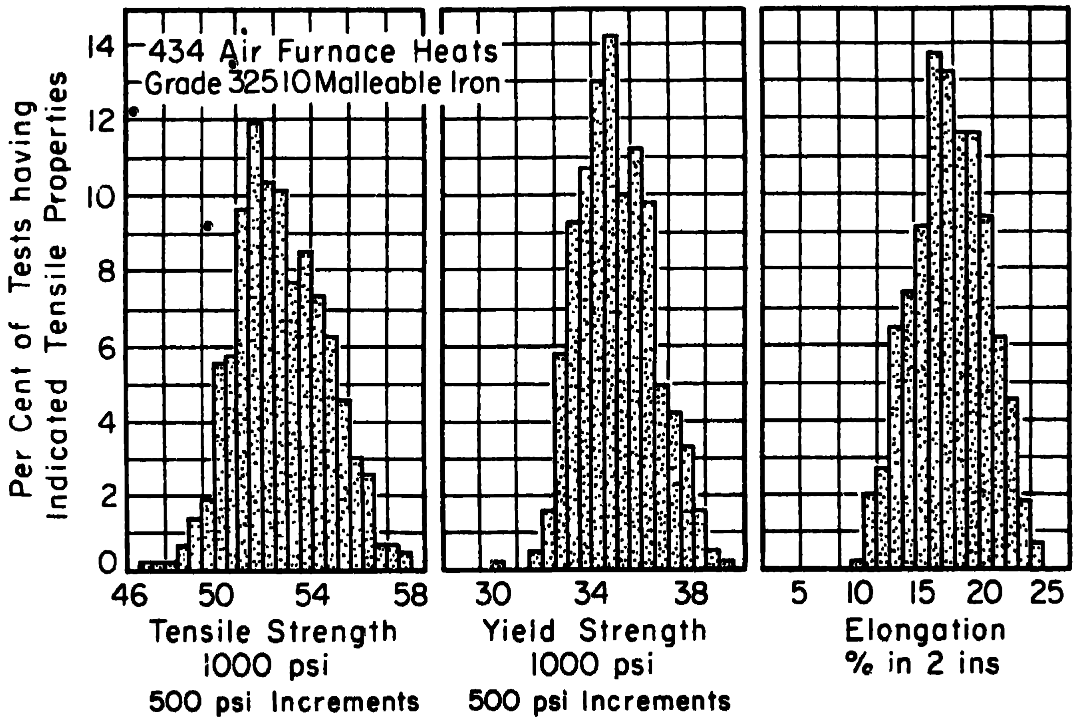


Fig. 10. **Tensile test records of 434 air-furnace heats of Grade 32510 standard malleable iron.**

EFFECT OF MACHINING: MACHINED AND AS-CAST TEST BARS

The supposition is occasionally voiced that the valued tensile properties of malleable iron depend principally on the surface metal or skin of the casting. The idea was undoubtedly a carryover from whiteheart malleable practice which involves decarburization, as distinguished from blackheart malleable production, in which the carbon is converted from the combined to the free nodular form rather than removed. Removal of the surface metal by machining or grinding blackheart malleable, a number of independent investigations have shown, does not deleteriously affect tensile or yield strength, the average effect being up to 3 to 5 per cent. Machining malleable iron test bars, which are of the same composition and have been heat-treated similarly, is likely to produce greater uniformity in tensile test values. In general, machining such bars results in a slight decrease in tensile values, but the variation is not greater than that normally encountered in day-to-day operation in most well controlled production processes.

These generalizations are based on findings both from a number of studies made during the past forty-odd years[12,22,37,38,39,40,41,42] and from an investigation[43] conducted specifically for this Handbook and employing a sample large enough for thorough statistical analysis.

This investigation was concerned with the mechanical properties of 35018 malleable iron as produced by one foundry. Standard bars were tested in both the machined and as-cast condition in groups of ten from ten different heats. All the bars cast for this series were 5/8-inch in diameter. From them, machined specimens of 0.505-inch diameter over a 2-inch gage length were prepared. Twenty bars from each heat, a total of 200, were required for this part of the experiment.

In addition to the effect of machining, the mechanical properties of samples from sections of different size were also studied. One of the ten heats contained three groups of ten samples in addition to the two groups mentioned above; that is, a total of 50 bars were made from this heat. One set of ten specimens was ground after machining. Another set was

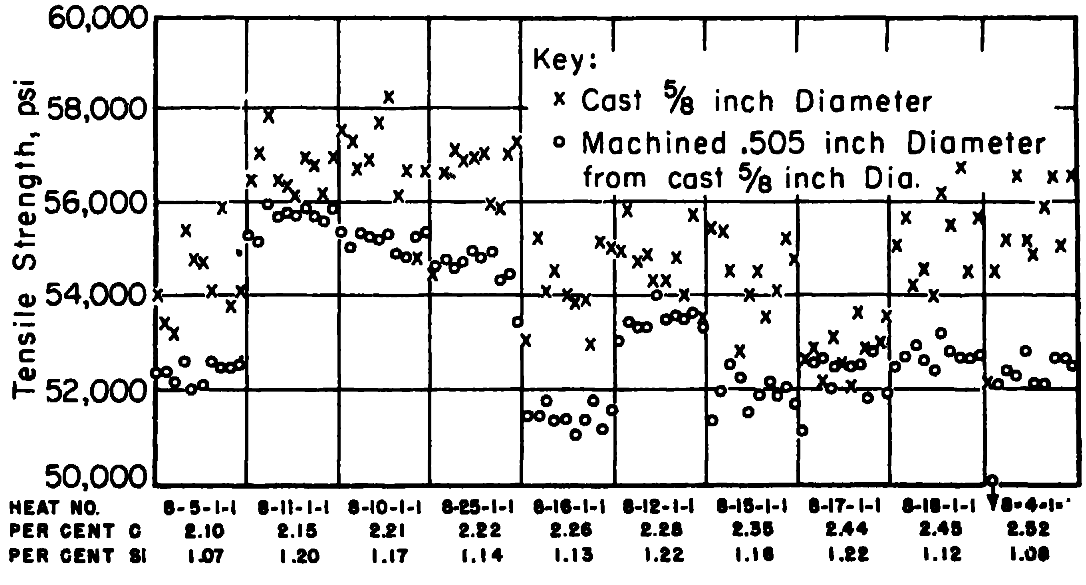


Fig. 11. **Tensile strength test results for ten heats of standard malleable iron, comparing unmachined and machined specimens at various carbon and silicon levels.**

cast with ¾-inch diameter sections. A third group consisted of standard 0.505-inch diameter specimens machined from cast test bars of ¾-inch diameter. The carbon content of the heats ranged from 2.10 to 2.52 per cent. Silicon varied from 1.07 to 1.22 per cent. All other elements remained essentially constant. Table 2 shows the average mechanical properties obtained in each of the 23 groups of ten test bars, with the chemical composition of each heat. Figure 11 presents tensile strength results.

TABLE 2. AVERAGE MECHANICAL PROPERTIES OF TEN HEATS

					*Chemical Analysis**		
Heat Number	*Tensile Strength (p.s.i.)*	*Yield Strength (p.s.i.)*	*Per cent Red. Area*	*Per cent Elong.*	*C. %*	*Si. %*	*Mn. %*
		Machined to .505" from ⅝" cast					
8-5-1-1	52,480	33,960	18.2	19.7	2.10	1.07	0.27
8-11-1-1	55,810	36,500	25.6	26.0	2.15	1.20	0.29
8-10-1-1	55,340	36,580	24.3	23.9	2.21	1.17	0.31
8-25-1-1	54,720	37,400	22.8	22.8	2.22	1.14	0.31
8-16-1-1	51,570	33,680	22.1	24.1	2.26	1.13	0.24
8-12-1-1	53,630	35,650	20.1	22.8	2.28	1.22	0.24
8-15-1-1	52,090	34,580	20.9	23.6	2.35	1.16	0.21
8-17-1-1	52,430	35,210	15.9	19.3	2.44	1.22	0.22
8-18-1-1	52,920	35,750	19.4	21.9	2.45	1.12	0.24
8-4-1-1	52,280	34,490	18.9	21.1	2.52	1.08	0.28
			Cast ⅝"				
8-5-1-1	54,440	34,840	19.6	16.9	2.10	1.07	0.27
8-11-1-1	56,860	36,550	23.8	24.4	2.15	1.20	0.29
8-10-1-1	57,040	36,830	21.5	23.2	2.21	1.17	0.31
8-25-1-1	56,700	36,630	20.0	22.0	2.22	1.14	0.31
8-16-1-1	54,320	34,560	19.9	21.1	2.26	1.13	0.24
8-12-1-1	54,880	35,760	20.2	21.1	2.28	1.22	0.24
8-15-1-1	54,510	34,440	18.2	18.6	2.35	1.16	0.21
8-17-1-1	52,990	33,250	17.2	19.4	2.44	1.22	0.22
8-18-1-1	55,430	36,350	16.6	18.3	2.45	1.12	0.24
8-4-1-1	55,470	35,190	17.6	20.6	2.52	1.08	0.28
		Ground to .505" from ⅝" cast					
8-25-1-1	54,870	37,390	23.6	24.2	2.22	1.14	0.31
		Machined to .505" from ¾" cast					
8-25-1-1	53,775	35,490	21.0	22.0	2.22	1.14	0.31
		Cast ¾" unmachined					
8-25-1-1	56,270	36,000	19.8	22.7	2.22	1.14	0.31

*** Sulfur 0.08, phosphorus 0.162, which are typical for all heats.**

Statistical analysis of these data indicated a statistically significant difference in tensile strength—3 to 4 per cent—but not in yield point or strength (offset method), reduction of area, or elongation among the ten heats employed in the study. On the basis of the experimental results, it was concluded that the difference in mechanical properties between machined and as-cast specimens is negligible, unless the periphery of the cast bars contains minor surface imperfections, decarburization, or a small amount of pearlite near the surface, which is removed by the machining or grinding operation. These surface conditions in turn will depend on the composition of the metal cast, the melting practice, and mold properties, the heat-treating practice (including type of equipment and furnace atmosphere) and the method of cleaning. Grinding ⅝-inch diameter test bars to 0.505-inch apparently produced no different effect on mechanical properties from that given by machining bars to 0.505-inch diameter. Tensile test results are in good agreement for bars cast from the same heat and similarly processed, and are sufficiently sensitive to demonstrate composition and manufacturing variables that may occur from heat to heat.

EFFECT OF SECTION ON TENSILE TEST VALUES

With some cast metals, the diameter of the specimen used in tensile tests is of great importance, higher tensile properties being shown if specimens of smaller diameter are used.[5,22,44,45] This results from the fact that when the casting is cooling in the mold, light sections cool much more rapidly and consequently have a finer grain. With malleable iron, specimen diameters have less effect on tensile test results. This is due to the fact that the structure of malleable iron is influenced more by the heat-treatment essential in its production than by the preceding solidification process. In the study[43] of machined and as-cast bars mentioned above, no significant difference was found between the mechanical properties determined from ¾-inch cast specimens and those determined from ⅝-inch cast specimens. Similarly, no differences appeared in the mechanical properties of machined specimens obtained from cast bars of ⅝- and ¾-inch diameter. The regularly specified test bar diameter of ⅝-inch is generally found to give dependable values for malleable iron as produced for use in commercial castings. In fact, in a study[38] of the tensile properties indicated by specimens cut from the malleable iron castings themselves, as compared with properties determined by separately cast test bars, it was reported that the mechanical properties of the castings as determined by the former showed from 90 to 95 per cent of the values given by the latter. By contrast, in other cast materials marked deviation is often found between test specimen results and those from specimens cut from castings.

In another study, test specimens were machined from standard malleable iron blocks 3½ by 14 inches and of various thicknesses, and the results of tests on them were compared.[46] The tensile strength, yield strength, elongation, and reduction of area of bars taken from tellurium-treated blocks 3 inches thick closely matched the properties obtained from ¾-inch sections. This is testimony not only that malleable iron can be produced in the heavier sections but also that no impairment of properties occurs in going from light to heavy sections.

Effect of Chemical Composition on Tensile Test Values

The tensile properties of standard malleable iron vary inversely with the carbon content, particularly at levels of 2.43 per cent and greater total carbon.[47] Tensile strength and elongation in the investigation discussed above[43] were found in general to decrease with increasing carbon content. Other elements present in the iron, and the method of processing the metal also have some influence on tensile properties. For thorough discussion of the effect of chemical composition on the properties of malleable iron, the reader is referred to Chapter XI, "The Metallurgy of Malleable Iron."

Modulus of Elasticity in Tension

The modulus of elasticity in tension, (also called Young's Modulus), the ratio of unit stress to unit strain, is a measure of the rate of stretch of a metal within its elastic limit. The higher the modulus of elasticity, the stiffer the metal. Stiffness of a casting is also affected by design, but, in general, a metal with a high modulus of elasticity has more rigidity than one with a low value. The modulus of elasticity of malleable iron is approximately 25,000,000 p.s.i.

Poisson's Ratio

A material stressed in tension or in compression within the elastic limit alters its cross section, elongating and becoming thinner or shortening and becoming thicker. The ratio of unit lateral deformation to unit longitudinal deformation of a material thus stressed is called Poisson's Ratio. For malleable iron Poisson's Ratio is 0.17.[26]

HARDNESS

The hardness of malleable iron is most commonly measured by the Brinell hardness test, using a 3,000 kilogram load on a 10-mm. diameter ball of hardened steel or tungsten carbide. Standard malleable iron hardnesses fall within the range of 110 to 156 Brinell hardness number (BHN).

The microstructure of malleable iron consists of ferrite and temper carbon. Since the graphite nodules contribute little to strength or hardness, the hardness of malleable iron is attributable to the ferrite. Hence, when solution-strengthening elements (e.g. silicon or copper) are carried in the ferrite at relatively high concentrations, the hardness of such malleable castings will be in the upper portion of the above-mentioned range.

The 10-mm. diameter ball of the Brinell tester is sufficiently large to cover a number of grains of ferrite and nodules of temper carbon. Thus the Brinell test should represent a good average hardness of the gross structure under test. As with all hardness test methods, it is desirable to have a smooth, flat surface on which to make the impression. The specimen in all hardness testing must be rigidly supported to prevent deflection, with its surface normal to the load. The thickness of the casting to

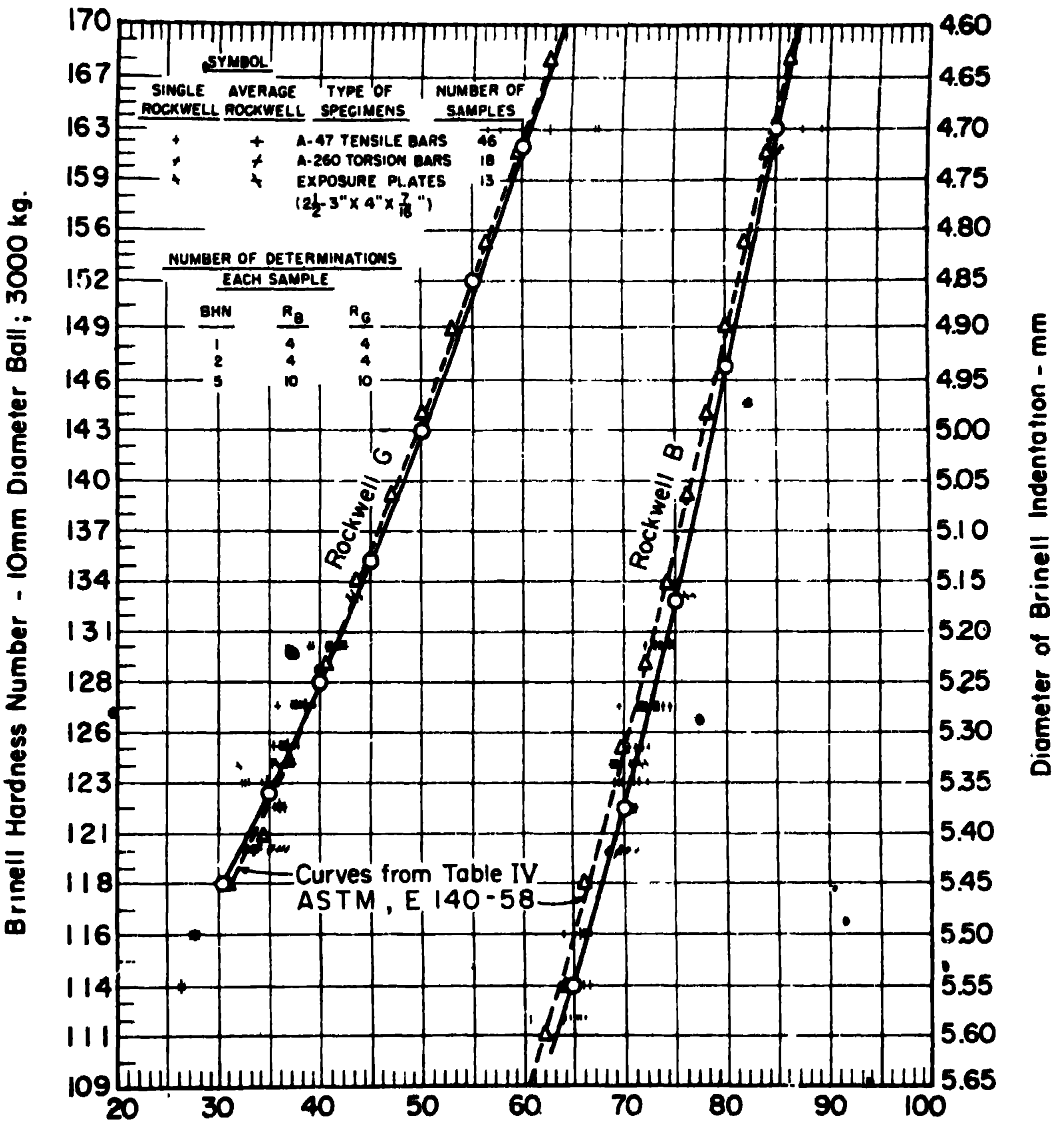


Fig. 12. **Chart for conversion from Brinell to Rockwell *B* and *G* scales,[55] based on original work conducted for this handbook on malleable iron specimens.**

be tested should be at least ten times the depth of the indentation, and the distance between center of indentation and edge of specimen should be at least two and one half times the diameter of the indentation. Tables for converting measured impression diameters into Brinell hardness numbers are given in the Appendix.

For smaller malleable castings than would comply with the above requirements for the Brinell tests, it is possible to employ the Rockwell test using the B scale preferably, or the G or K scale. Approximate conversion from Rockwell B or G to Brinell hardness numbers may be found in Fig. 12. As can be seen, the hardness of standard malleable irons falls usually within the range of 65 to 83 Rockwell B. Since the Rockwell method involves only a very small (1/16-inch diameter) penetrator under loads of 100 and 150 kilograms, respectively, for the B and G scales, a single test may fall more on one structural constituent than on the other and so would not necessarily represent the over-all hardness of the casting. Therefore, it is very desirable to take multiple readings on a well-prepared surface of each specimen when using the Rockwell test. This method may also be utilized to advantage in testing hardened malleable irons, as well as in checking small pearlitic malleable castings, as is discussed in Chapter VI, page 123.

FATIGUE PROPERTIES

In many applications, malleable iron castings are subjected to dynamic loading, which may cycle either regularly or in an erratic, transient manner. If heavily loaded in this way, all materials will fail at lower stress values than they would had they been only under static loading over the same period of time. Failures caused by cyclic stresses are generally characterized by their progressive nature and by the absence of plastic deformation near the fracture. Such failures are attributed to the phenomenon called fatigue. It becomes obvious that for parts which are to be highly dynamically loaded in service, the fatigue properties may be of greater significance than other properties, such as static, tensile strength or hardness values.

Various types of loading methods are used in fatigue testing.[279] These include axial loading in tension and/or in compression, torsional loading, and loading by reverse bending of a flat specimen or a rotating beam. On the average, fatigue life is increased by reducing the applied stress. For ferrous materials, the curve for stress versus cycles to failure (the S-N curve) changes slope rapidly between one and ten million cycles so that a small reduction in applied stress results in a very large increase in life. Frequently, specimens enduring ten million cycles are considered "runouts," which would last practically infinitely.

Fatigue limit (or endurance limit) is defined[283] as the limiting value of the stress below which a material can presumably endure an infinite number of stress cycles; that is, the stress at which the S-N diagram becomes horizontal and appears to remain so. Because considerable scatter is characteristic of fatigue data, statistical methods are best used for analyzing and applying the results of fatigue tests. Investigators may report the average, median, or possibly the shortest life of a few samples tested at a given load. In practice, the shortest life of a large number of samples may be the most significant, and this value may be considerably lower than anticipated from the results of a few test specimens. A more comprehensive discussion of the statistical procedures employed is given in references 280 and 281.

The *fatigue strength* is the greatest stress which can be sustained for a given number of stress cycles without fracture. The ratio of fatigue limit (or fatigue strength) to the static tensile strength is called the *fatigue ratio*. This value is not constant for various stress levels and for

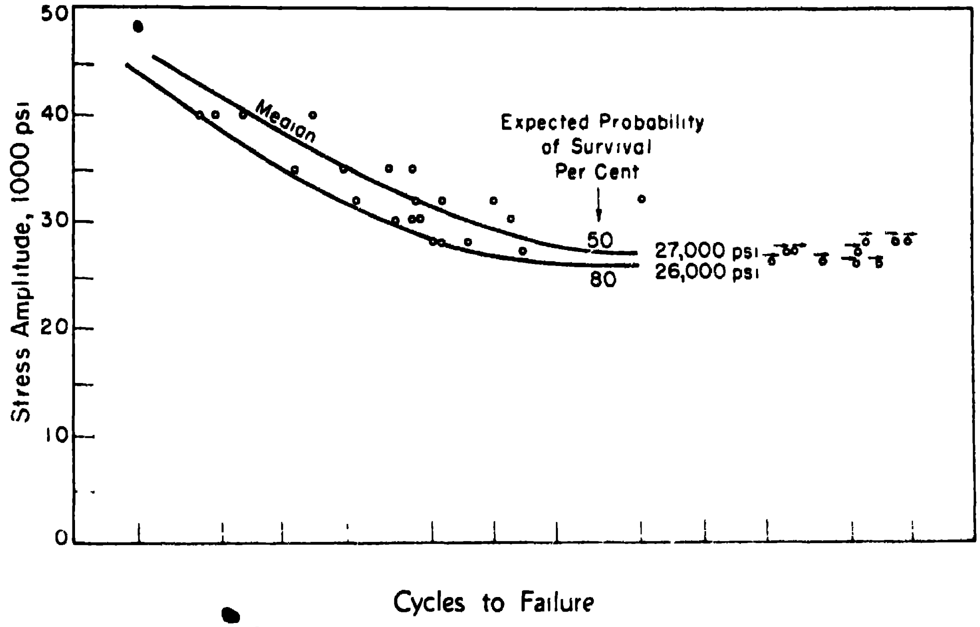


Fig. 13. **Probability-stress-cycle curve for Grade 35018 malleable iron.**

differently-designed test specimens, so it must be used with qualifications.

Fig. 13 shows a probability-stress-cycle (P-S-N) curve[280] for grade 35018 malleable iron.[284] A Krouse high-speed cantilever machine[285] was used with polished, unnotched 0.20-inch diameter specimens. At least four specimens were tested at each load in order to determine the spread in the data and to permit estimation of the probability of survivorship. The scatter shown in this graph is typical of fatigue test results, even though polished specimens were used and extreme care was exercised in measuring the specimen diameter and setting the stress. The variability shown in Fig. 13 emphasizes the need for statistical interpretation of fatigue data. The scatter in the life of actual parts, operating in varying environments, can be expected to be much larger. The median fatigue limit for the data in Fig. 13 is estimated to be greater than 27,000 psi. while the fatigue limit for eighty per cent survival is approximately 26,000 psi. The fatigue ratio for these series of tests averaged approximately 0.50.

The results of three other independent investigations are summarized in Table 3. Typical fatigue ratios for malleable iron and a number of other ferrous materials are compared[51] in the bar graph of Fig. 14. It is apparent that malleable iron possesses very favorable fatigue properties.

Notch Sensitivity

Fatigue test data are generally obtained with highly polished specimens in order to reduce scatter. Rough or corroded surfaces can greatly reduce fatigue strength, particularly at higher strength and hardness levels.[282] Castings are seldom, if ever, polished to the same degree as

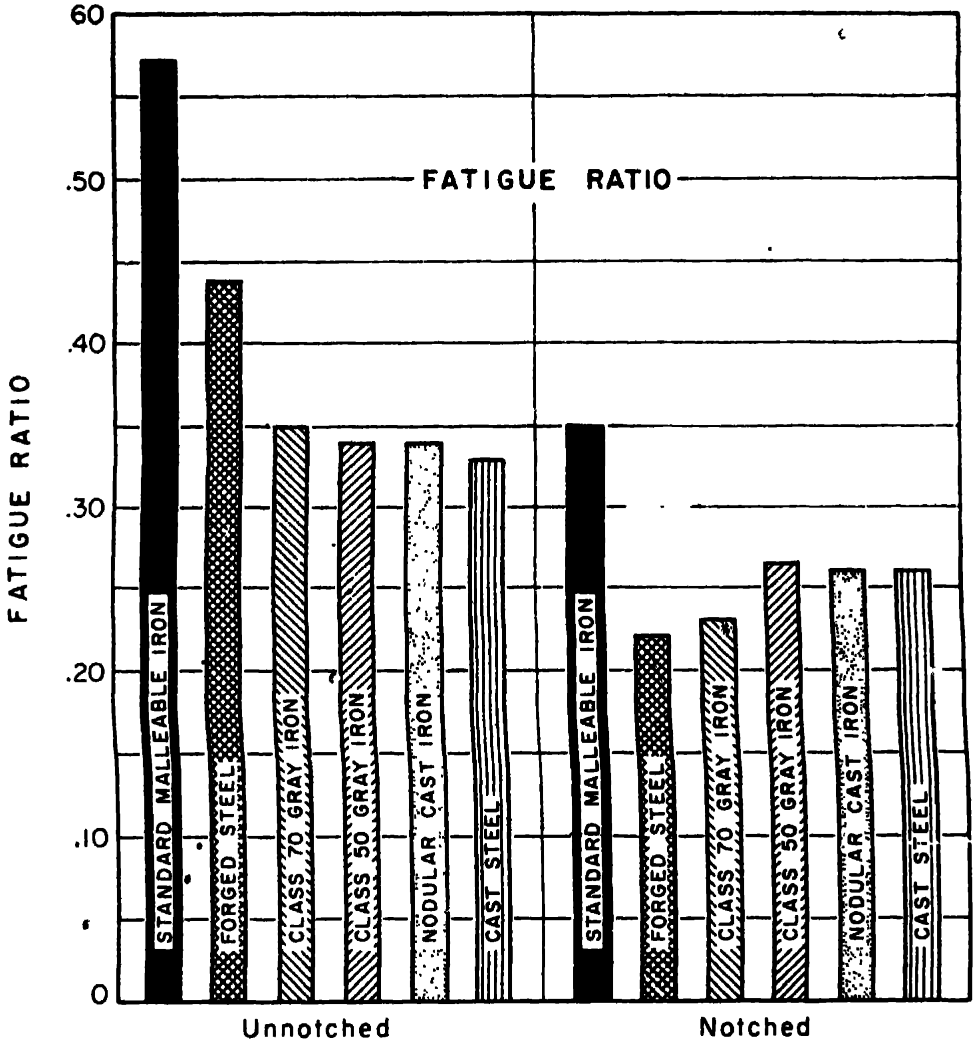


Fig. 14. **Fatigue ratios of various ferrous alloys.**

fatigue test specimens, so some measure of the effect of notches or surface irregularities on the fatigue life is important. Any notch, sharp corner, or discontinuity in a part can cause a stress concentration. It is generally at the site of such stress raisers that fatigue cracks originate, ultimately progressing across the entire section.

The *fatigue strength reduction factor,* or fatigue notch factor, K_f, is the ratio of the fatigue strength of a member or specimen with no stress concentration to the fatigue strength with stress concentration. The more this figure approaches unity the less sensitive is the condition to fatigue failure. Measured K_f values have been observed to vary with (1) material, (2) severity of notch, (3) type of notch, (4) type of loading, and (5) severity of loading.[77] Therefore, the fatigue notch factor has no significance unless these conditions are stated.

In studying the effect of notch design on the fatigue notch factor, one investigation[286] employing a rotating beam machine developed the following results for grade 32510 malleable iron specimens with 60-degree V-notches:

Specimen Diameter (inch)	*Notch Dimensions (inch)*		*Fatigue Strength (psi.)**	*Fatigue Notch Factor (K_f)*	*Fatigue Ratio*
	Base Radius	*Depth*			
0.300	——Unnotched——		26,000	..	0.49
0.505	0.005	0.028	15,500	1.7	0.29
0.505	0.010	0.028	19,750	1.3	0.37
0.505	0.030	0.030	16,000	1.6	0.30

*** Presumed to be median fatigue strength, representing complete reversal of this stress in each direction.**

When the depth of the notch was increased from about 0.03-inch to about 0.08-inch, the fatigue strength of specimens with a 0.010-inch radius at the base of the 60-degree notch was essentially unchanged. However, similar changes in the depth of notches in the specimens having 0.005-inch and 0.030-inch radii at the base of the notch caused the fatigue strength to fall off to 9,500-10,000 psi. and the fatigue notch factor, K_f, to increase to 2.6-2.7.

TABLE 3. FATIGUE PROPERTIES OF SOME FERRITIC MALLEABLE IRONS (UNNOTCHED)

No.	*Type Iron*	*Tensile Strength (psi.)*	*Fatigue(a) Limit (psi.)*	*Fatigue(b) Ratio*
1	Medium Carbon[286]	53,000	26,000	.50
2	High Carbon[50]	45,000	28,000	.60
3	Medium Carbon[50]	53,000	32,000	
4	Low Carbon[50]	54,000	36,000	
5	High Carbon[49]	50,000	20,000	.40
6	Medium Carbon[49]	53,000	26,000	.50
7	Low Carbon[49]	58,000	33,000	.55

Notes:

(a) Presumed to be median fatigue limit in all cases.

(b) Because of statistical uncertainty in both the tensile strength and fatigue limit, fatigue ratios are reported to the nearest 0.05.

RESIDUAL STRESS:

The presence of residual stresses must be considered in applications involving fatigue. Normally, malleable iron castings are free from residual stress because of the annealing treatment employed in their manufacture. It is known that in the proper location residual compressive stresses can improve the fatigue life appreciably. Such stresses can purposely be impressed into critical areas through adequate shot blasting, rolling of fillets, tumbling, over-stressing (loading above the yield strength), or coining.

Employing a special cantilever fatigue specimen loaded in one direction with a stress amplitude of 36,000 psi. and a mean stress of 23,000 psi., one investigator[49] dramatically demonstrated the beneficial effect of shot peening on malleable iron. The average life of peened specimens was five times that of non-peened ones, and the lowest of eight peened specimens lasted nearly three times as long as the highest of eight non-peened samples.

DAMPING CAPACITY

Damping capacity is defined as the ability of a material to absorb vibrations, changing mechanical energy into heat. It is chiefly a function of material and stress level. This property, when expressed as the ratio (in per cent) of the energy dissipated in a cycle to the energy of that cycle is called the specific damping capacity.

In an investigation[54] carried out especially for this handbook, the specific damping capacity of a number of cast ferrous materials was determined by measuring the logarithmic decrement in amplitude of specimens 1 inch by 6 inches by ⅛-inch. Each specimen was subjected to known stresses by bending, and was then suddenly released. It may be seen from Table 4 that malleable iron has about three times the damping capacity of cast steel and about twice that of nodular irons.

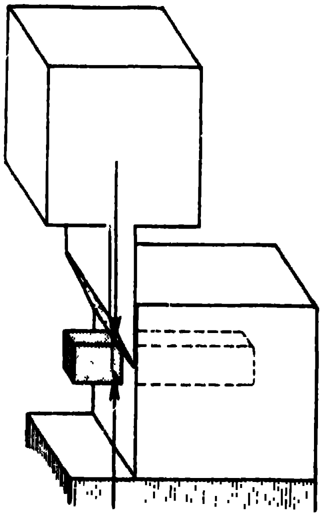
TABLE 4.

SPECIFIC DAMPING CAPACITY IN PER CENT OF VARIOUS CAST FERROUS ALLOYS

Stress Level, p.s.i.	15,000	30,000
Malleable Iron	4.20	6.30
Pearlitic Malleable Iron	3.30	4.55
Ferritic Nodular Iron	2.50	3.30
Pearlitic Nodular Iron	2.20	2.95
Cast Steel (Grade B)	1.45	1.90

At very low stress levels, i.e., a few hundred p.s.i., high-strength gray irons were found to be comparable to malleable in damping capacity. While soft gray irons have very good damping properties, they must be restricted to only those applications in which a low-strength brittle material is not objectionable.

SHEAR STRESS



Specimen Loaded in Shear

A shearing stress, such as that exerted by a scissors or a guillotine cutter, produces in the particles of the stressed material a tendency to separate by sliding against each other. It occurs, for example, when two equal and opposite forces act at right angles to a bar and very near together. It acts in a transverse plane of the stressed material. The shear strength of a material is the maximum shearing stress which it is capable of carrying based on original area of cross section. In torsion tests, the ratio of the unit shear stress to the angular displacement, caused by it, per unit length within the elastic range, times ¼, is the modulus of elasticity in shear, or the modulus

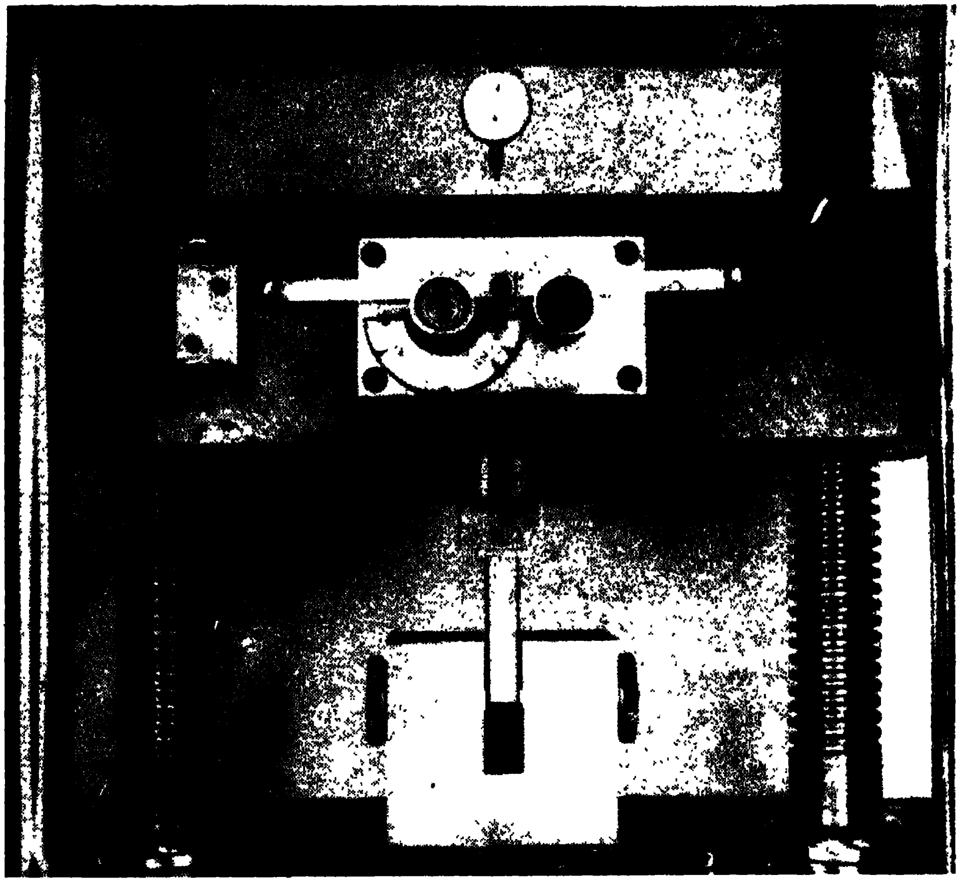


Fig. 15. Shear specimens of standard malleable iron 2 inches long and 0.505 inches in diameter were tested in a machine of the design shown in the photograph.

of rigidity. Representative values established by four different investigators[22] for the properties of standard malleable iron in shear are as follows:

Shear strength	48,000 p.s.i.
Yield strength in shear	23,000 p.s.i.
Modulus of elasticity in shear	12,500,000 p.s.i.

In studies[55] made especially for this handbook, employing the equipment

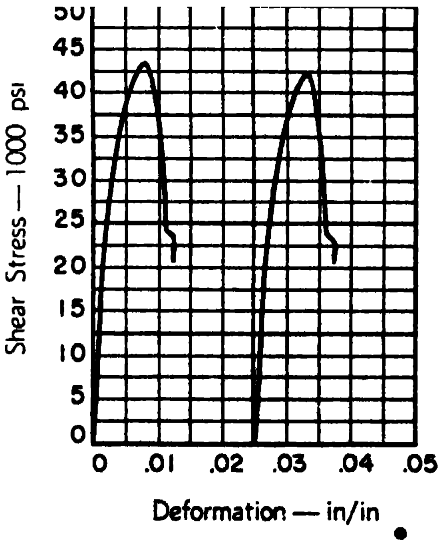


Fig. 16. Autograph of the shear test on malleable iron using the equipment shown in Fig. 15.

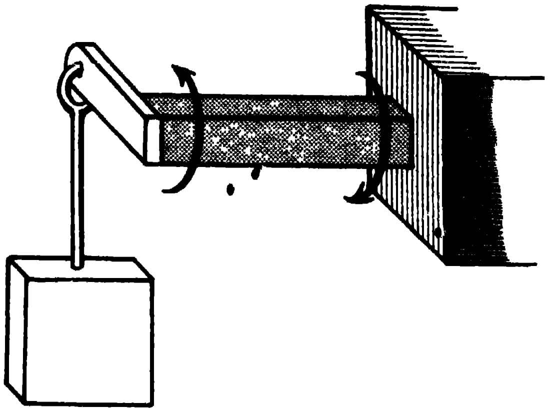
pictured in Fig. 15, shear specimens of standard malleable iron, 2 inches in length and 0.505-inch in diameter, were used. Average tensile values for these were as follows:

Tensile strength	53,225 p.s.i.
Yield point	36,650 p.s.i.
Elongation	17.5 per cent in 2 inches

The shear strength average in these tests was 43,020 p.s.i., and the average yield shear strength was 21,510 p.s.i. The shear strength of standard malleable iron is seen to be approximately 80 per cent of the tensile strength. The shear test autograph of this study is given in Fig. 16.

TORSIONAL STRENGTH

The resistance of a metal to being twisted about an axis is its strength in torsion. It is calculated from the load applied to produce rotation, the distance from the axis to the point of load application, and the length of the specimen. Average values obtained from six 35018 standard malleable specimens of 0.750-inch diameter and 4-inch gage length, in research conducted for this handbook,[56] are as follows:



Specimen Loaded in Torsion

Torsional strength (modulus of rupture)	54,100 p.s.i.
Yield strength in torsion	19,035 p.s.i.
Angle of twist at rupture	543 degrees, 0.750-inch diameter bar, 4-inch gage length, 136 degrees per inch

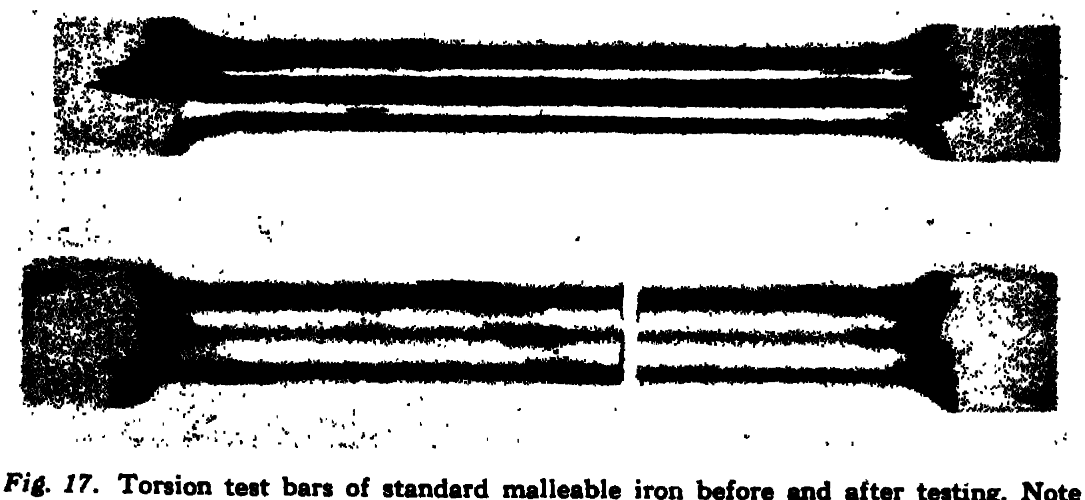


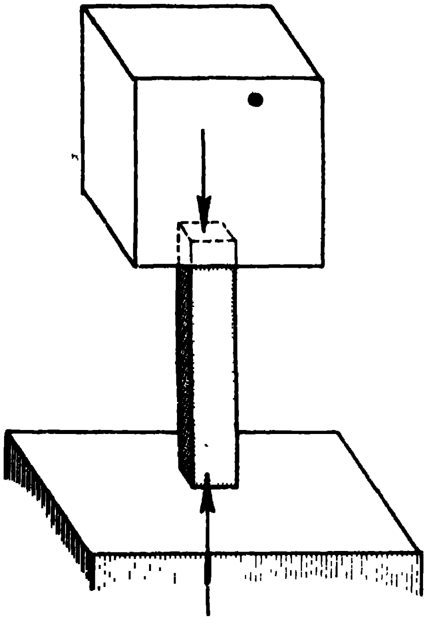
Fig. 17. **Torsion test bars of standard malleable iron before and after testing. Note the degree of distortion as indicated by the black spiral on the lower bar.**

Average values reported for standard malleable iron by two other investigators[22a] are:

Torsional strength (modulus of rupture)	58,000 p.s.i.
Yield strength in torsion	24,850 p.s.i.
Angle of twist at rupture	360 degrees, 0.9-inch diameter bar, 5-inch gage length, 72 degrees per inch; 790 degrees, 1.0-inch diameter bar, 10-inch gage length, 79 degrees per inch

Torsion test bars before and after testing are shown in Fig. 17. A practical example of the ductility of malleable iron as expressed in torsional strength is its ability to be bent or twisted without fracture.

COMPRESSIVE STRENGTH



Specimen Looded in Compression

Compression, the reverse of tension, is produced by equal and opposite forces directed toward each other in a plane normal to the surface of the material under stress. In the compression testing of metals, a solid cylindrical specimen whose length is three times its diameter is commonly employed, the load being applied in line with the axis of the specimen. The compressive strength of the material is the maximum compressive stress which it is capable of sustaining, based on original area of cross section. Brittle materials, when tested in this form, yield under compression by bulging slightly at the center and then shattering, thus giving exact determination of the breaking load. Standard grades of malleable iron, being ductile and capable of great plastic deformation, do not shatter under compression but gradually deform, until, at extreme loads, fracture occurs. Specimens from two studies made for this handbook are pictured in Figs. 18 and 19. Figure 18 shows a test specimen of standard malleable iron, turned from the end of a regular A.S.T.M. tensile test bar having 1-inch diameter ends. The compression specimen was turned to 0.798-inch diameter and was 2 375 inches in original length. Tested to 60,000 p.s.i., it did not fracture, but was squeezed to a final length of 1.741 inches, a reduction in length of 26.7 per cent. Tensile test results given by a companion tensile test bar were: tensile strength 54,700 p.s.i.; yield point 37,500 p.s.i.; elongation 22.5 per cent in 2 inches.

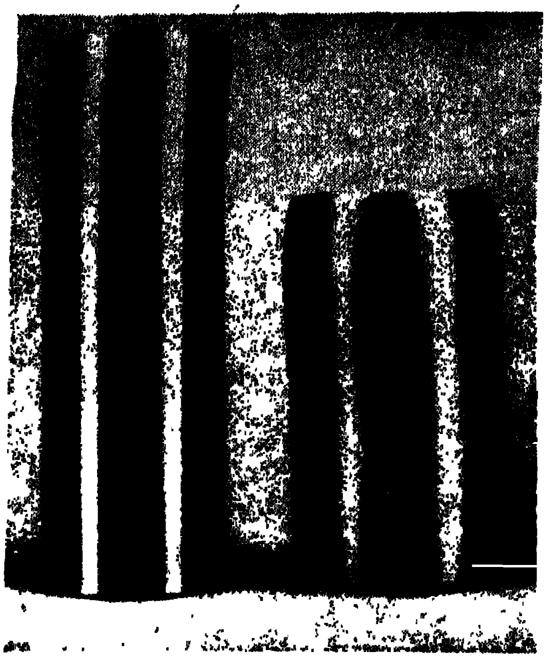


Fig. 18. **A compression test specimen of Grade 35018 which was turned from the end of a standard tensile test bar (left). The bar on the right has been partially deformed.**

Fig. 19. **Standard malleable iron tested to destruction in compression.**

Figure 19 shows results when standard malleable iron was tested to destruction in compression. Two cylindrical specimens were turned from an A.S.T.M. tensile test bar. Their original dimensions were 1.5 inches in

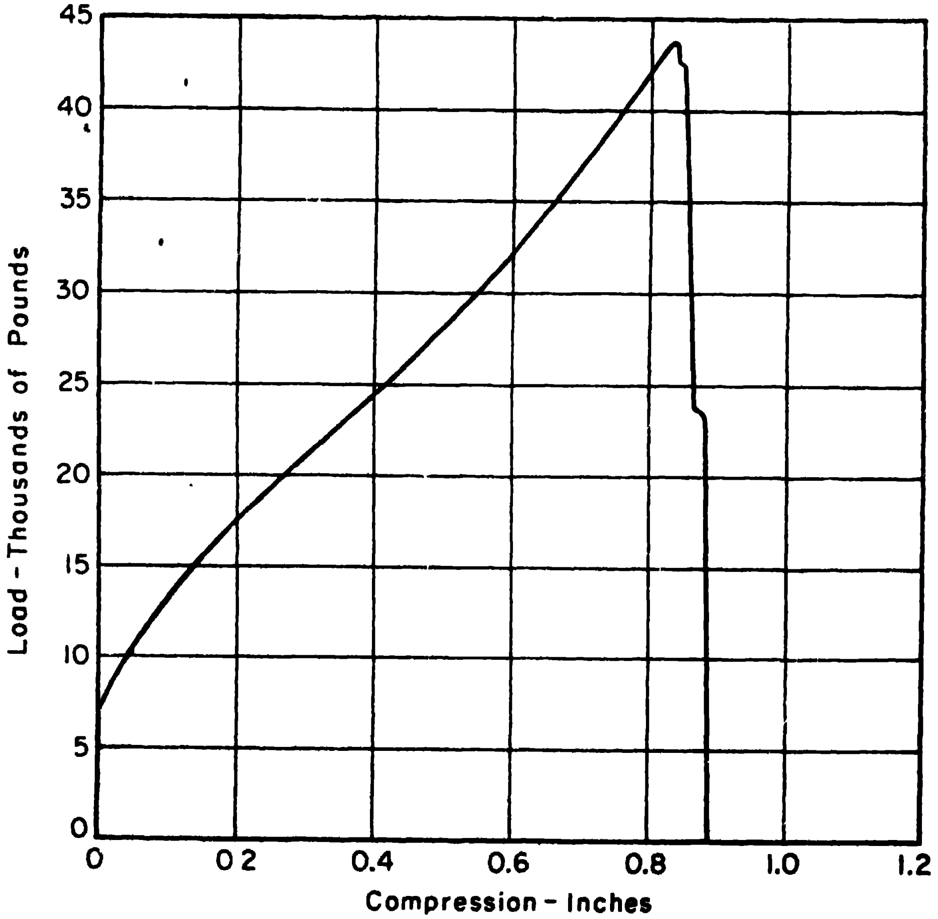
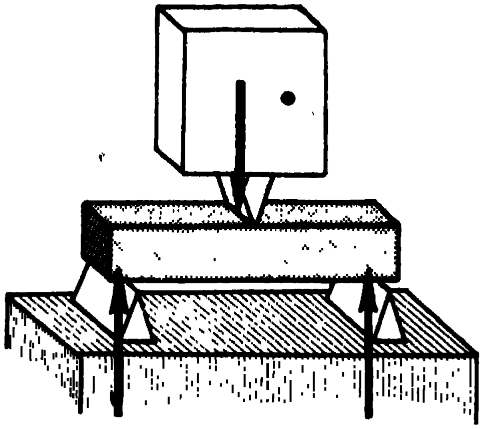


Fig. 20. **Compression test autograph for malleable iron.**

length, 0.5-inch in diameter. Breaking load for the specimen on the left was 44,000 pounds; its compressive strength was 219,000 p.s.i. For the specimen on the right, breaking load was 42,950 pounds, compressive strength 216,000 p.s.i., yield point 32,500 p.s.i., elongation 21 per cent in 2 inches. Graphic presentation of the test for the specimen on the left in Fig. 19 is given in Fig. 20.

Practically, there is a limit to the distortion which can be allowed to take place. Otherwise there will be interference with the service of the casting. The allowable compressive strength, therefore, depends on the design of the part itself and on the amount of distortion which can be tolerated. The modulus of elasticity in compression for standard malleable iron is very close to that in tension, or 25,000,000 p.s.i.



Specimen Loaded Transversely

TRANSVERSE STRENGTH

The transverse strength of a material is its resistance to deflection, or bending, by a load perpendicular to its longitudinal axis. In standard testing practice, the load is applied midway between two fixed supports. Transverse tests, like tests in compression, are seldom made on malleable iron or other ductile material, because these materials, before they break, will deform to an extent which make them unserviceable.

IMPACT RESISTANCE

Impact resistance[57,58] is the ability of a material to withstand shock. The foot pounds of energy absorbed, or the number of blows of a given intensity necessary to produce fracture are the values usually expressed. The two principal impact tests—the Charpy and the Izod—differ mainly in the fact that the test bar which is to be broken by the impact of a falling pendulum is supported as a simple beam in the Charpy testing machine and as a cantilever beam in the Izod machine. In each method, the test bar is usually notched in order that the stresses may be concentrated. The standard test bars used in Charpy and Izod tests are shown in Fig. 21.

Resistance to impact is one of the properties which have not as yet been reduced to a single test equally applicable to all metals. For some metals, including malleable iron, the notched specimens used in the Izod and Charpy tests give a dependable indication of impact resistance. For some others, which are more influenced by the concentration of stress at the notch, these tests are a truer measure of notch sensitivity than of im-

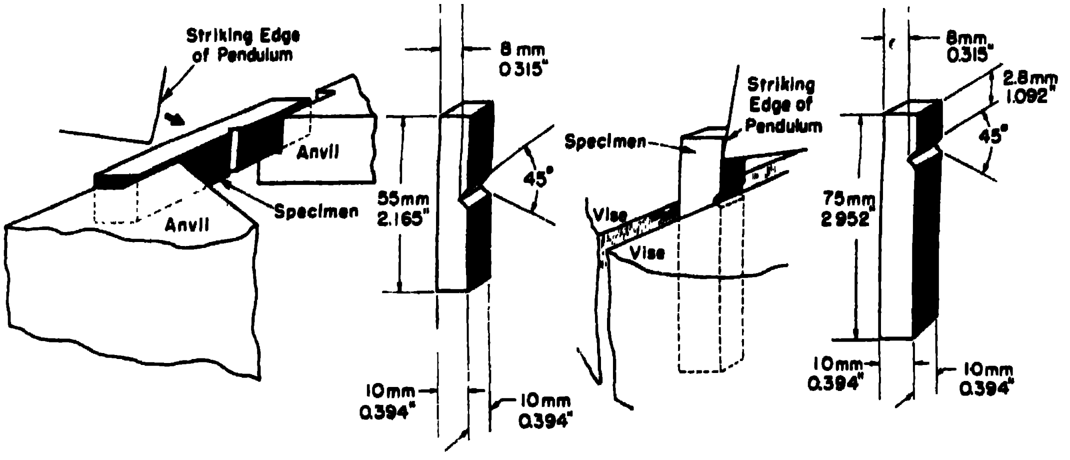


Fig. 21. **Arrangement of specimen in Charpy impact test with one type of test bar (left), and Izod impact test specimen and method of loading (right).**

pact resistance. The value of notched-bar impact tests has often been questioned on this ground.[39] This situation does not, however, mean that no importance should be attached to impact-test results. Generally speaking, more failures occur in metals which have very low Izod or Charpy impact values than in those which have high ones.[50] But the notched-bar test does not give accurate enough results on metals of different notch sensitivity to be entirely indicative of the metal's resistance to shock.

The impact resistance of Grade 35018 standard malleable iron, measured by the Charpy test using a notched, 0.394-inch-square bar, and 0.079-inch depth of notch, is about 16.5 foot-pounds.[12] In tests using a "keyhole" notch with 0.04-inch radius at bottom, a 0.390-inch-square bar, or a test bar with a V-notch 0.197-inch in depth, standard malleable iron shows impact resistance of 6.5 to 8.0 foot-pounds.[12] As measured by the Izod test, with a V-notch, 0.394-inch-square bar, and 0.079-inch depth of notch, the impact value of standard malleable iron is about 16.5 foot-pounds.[12] Impact tests employing standard Charpy V-notched specimens gave values in the range of 14 to 17 foot-pounds at room temperature for commercial heats of standard malleable iron.[46]

Unnotched round bars were used in another series of tests of the impact strength of standard malleable iron. Modified Charpy tests at room temperature, with bars being 0.505-inch in diameter and approximately 2.85 inches in length, gave room temperature values of 95, 73, 104, and 92 foot-pounds.[55]

The tensile impact test uses a test bar turned generally from a standard tensile test bar to a diameter of 0.236-inch and a gage length of 2 inches, as provided in A.S.T.M. specifications. The threaded ends of the bar engage the pendulum of the testing machine, and an impact block which strikes an anvil as the pendulum descends, and so stresses the bar.

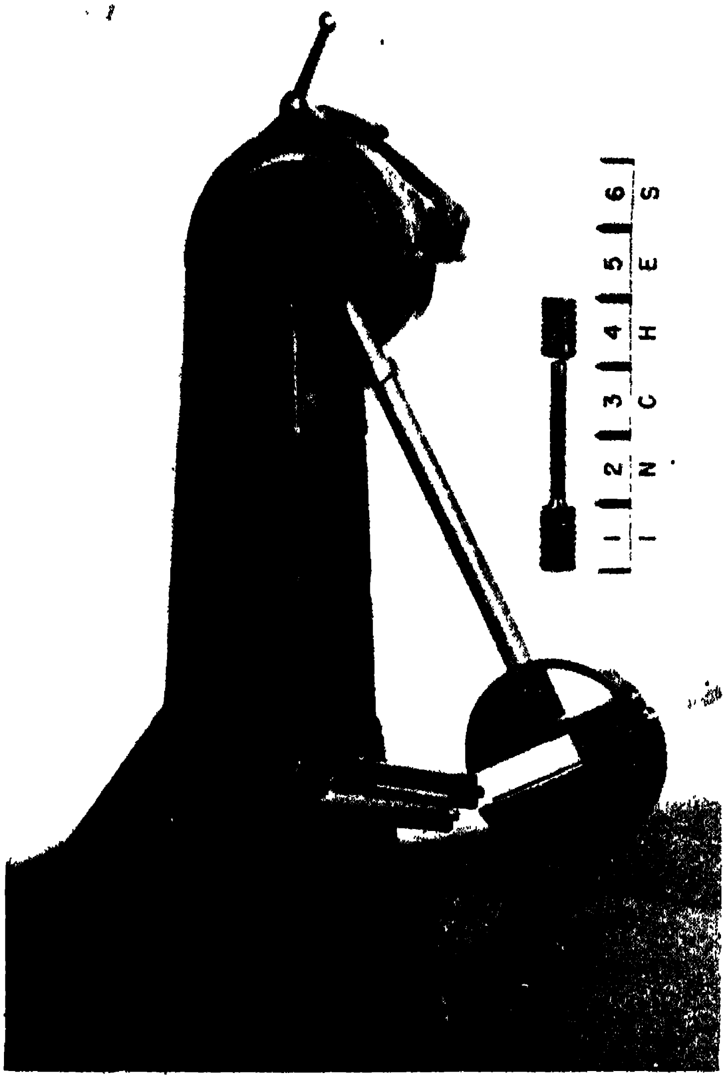


Fig. 22. Tensile impact testing machine and test bar. The test specimen is secured to the back edge of the pendulum and is fractured when the pendulum passes between two anvils at the bottom of its arc.

The form of the test bar and the manner in which it is used in the testing machine is shown in Fig. 22.

In tests with the machine at 200 foot-pound capacity and at room temperature, impact results[55] for representative standard malleable irons were as follows:

Tensile Properties			*Tensile Impact Strength (foot-pounds)*	*Impact Elongation (per cent)*
Tensile Strength (p.s.i.)	*Yield Point (p.s.i.)*	*Elongation (% in 2")*		
54,300	35,400	21.0	43.5	11
57,200	36,500	14.5	25.0	6

To determine the behavior of ferrous materials in the presence of a sharp notch or crack-starter—generally produced by the use of a brittle weld material on the surface of the specimen—the drop weight test[46] is employed. This uses a sample, approximately 3.5 by 14 by 1-inch, supported at each end, which is loaded by the impact of a falling weight with a spherical nose of about 1-inch radius. A stop between the specimen supports limits the deflection of the specimen to about 5 degrees of dynamic bend. The test seeks to ascertain whether the base material is capable of a small amount of deformation in the presence of a sharp notch. If it is not, brittle fracture occurs. The test establishes the critical nil-ductility point at which, after the development of a minute amount of deformation, the specimen breaks completely or remains essentially intact. The explosion bulge test[46]—in which a plate 14 by 14 by 1-inch containing a crack-starter weld is placed over a circular die and bulged by explosion loading—is used to investigate the relative resistance of a material to the initiation and propagation of fracture at temperatures above the nil-ductility transition temperature. The performance of standard malleable iron in both the drop-weight and the explosion bulge test indicates that it is not susceptible to brittle failure at room temperature.

The wedge test also is widely used in checking the impact resistance of standard malleable iron. In this test, the specimen is a wedge, six or seven inches long and one-inch wide, tapering from one-half-inch thick at the large end to $\frac{1}{16}$-inch at the thin end, represented in Fig. 23. With a hand hammer, about one-half-inch of the thin end of the wedge is bent over, starting a "curl," and the wedge is then held upright and firmly

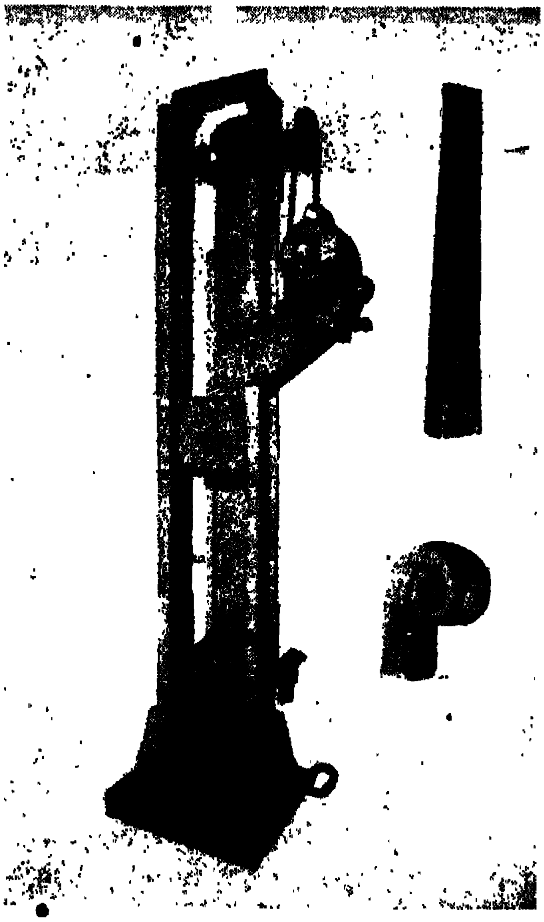


Fig. 23. **The motorized wedge tester with a wedge properly positioned for a test.**

fastened by the butt in a clamp forming part of an anvil. This is also shown in Fig. 23. It is then subjected to repeated blows of a 21-pound tup falling through a distance of 3½ feet, representing 70 foot pounds of energy. The tup strikes the curled edge of the wedge. The clamp is so made that the wedge can be titlted gradually permitting the tup to always strike on the highest point of the curl. As deformation of the wedge takes place, the distance through which the tup falls becomes greater, and the energy of the blow increases. The number of blows required to produce fracture is recorded, and is usually 17 or more. It is customary to end the test if no sign of fracture occurs after 30 blows. While this test is an arbitrary one, it gives a serviceable measure of the metal's ability to resist shock.

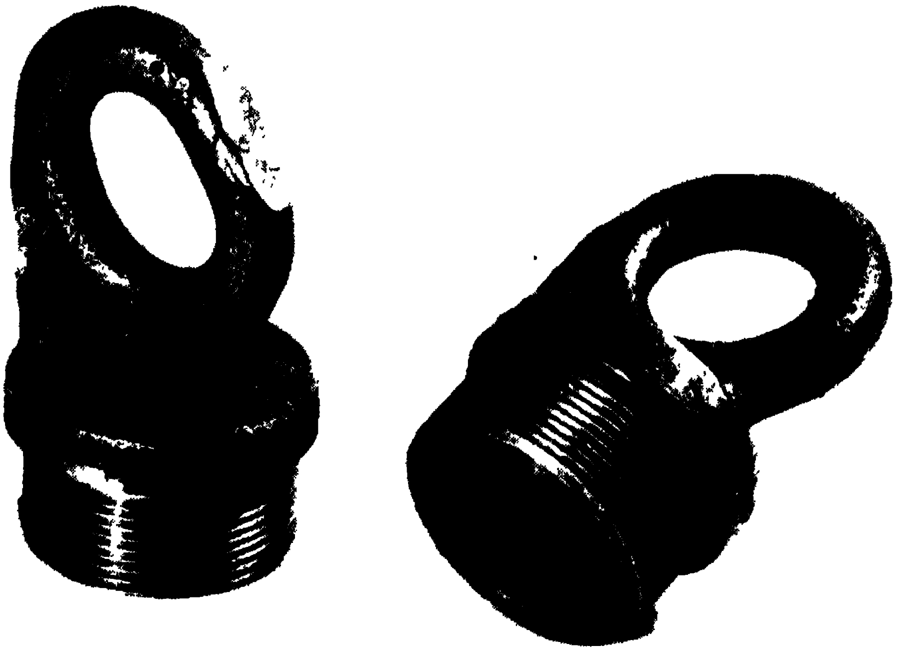


Fig. 24. **Standard malleable iron eyebolt lifting plugs before and after testing. Note flat spot on the tested casting to the left.**

EFFECT OF TEMPERATURE ON MECHANICAL PROPERTIES

Studies of the behavior of standard malleable iron at both high and low temperature demonstrate, in general, that the material is well suited to applications in a temperature range from -60 to 1200 degrees F. Low-temperature investigations have been concerned primarily with impact resistance and notch-sensitivity of the metal; high-temperature studies have focused principally on tensile strength, yield point, elongation, stress-rupture, and creep.

Standard malleable iron appeared fairly insensitive to temperature effects down to -80 degrees F. in a series of studies[60] employing Charpy

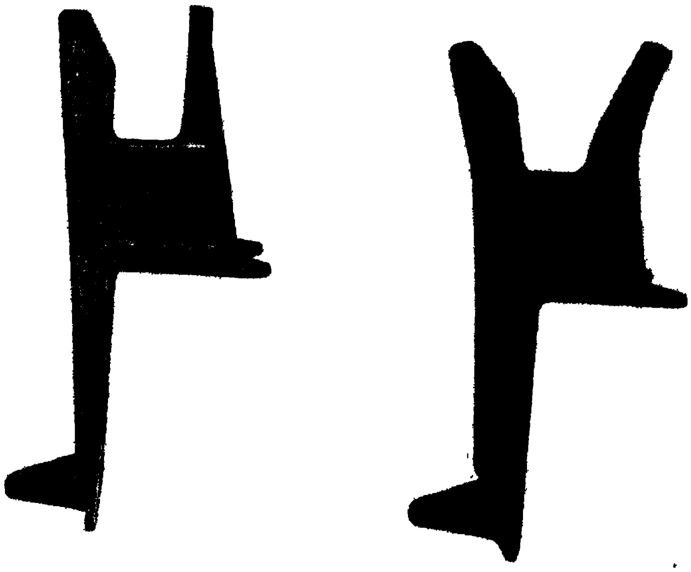


***Fig. 25.* A malleable iron casting before and after testing at –70° F.**

tests of notch bars, wedge tests, and tests of unnotched specimens. Tests of the impact resistance of standard malleable iron eyebolt lifting plugs of the sort shown in Fig. 24 were made by means of repeated blows of 70 foot-pounds in the standard wedge test machine from room temperature down to –40 degrees F. In this temperature range, it was found, the original $1\frac{1}{4}$-inch diameter of the eye of the plug could be deformed to $1\frac{1}{16}$ without fracture.[61]

Simulated service tests were conducted on sample castings of standard malleable iron, such as are shown in Fig. 25, which had an average metal section thickness of $\frac{1}{4}$-inch. Chilled to –70 degrees F., the castings were positioned under an inverted V-block and were struck by a small drop hammer, the blow being 60 foot-pounds. Temperature of the casting was checked after every second blow, and was maintained at –70 degrees F. After twelve blows, the mouth of the casting had enlarged by 50 per cent and had bottomed on the V-block, but the casting had not fractured.[42]

In a series of impact strength studies[55] conducted at different temperatures, modified Izod tests using bars 0.505-inch in diameter and approximately 2.85 inches in length, the following results were obtained:

10 degrees Fahrenheit	*–40 degrees Fahrenheit*	*–60 degrees Fahrenheit*
92 foot-pounds	90 foot-pounds	104 foot-pounds
78	77	72
110	106	96

Definitive quantitative data on the behavior of standard malleable iron under impact at low temperature in heavy as well as light sections resulted from notch-ductility studies of the material conducted at the Naval Research Laboratory.[46] In these, the drop-weight test was used to locate the nil-ductility transition (NDT) temperature—the critical point at which a ferrous material loses its ability to deform in the presence of a stress-raiser such as a sharp crack or a hard welded bead. Explosion tests of plates were used to establish relative resistance to the starting and propagation of brittle fractures at temperatures above the nil-ductility transition temperature, and Charpy V-notch transition curves were related to the behavior of the specimens in the preceding tests.

It was found that the NDT temperature of malleable iron increases proportionately with phosphorus content. Experimental lowering of phosphorus content below 0.01 per cent lowered the NDT values for standard malleable iron to –150 degrees F. Standard malleable iron's notch ductility is insensitive to section size. It has an NDT temperature of the order of –50 degrees F. in section sizes up to at least 3 inches thick. Properly made malleable irons, it was concluded, are inherently notch ductile and suitable for low-temperature applications. In comparison with "tonnage" steels, the ferritic malleable irons retain notch ductility to lower temperatures.

With rising temperatures, the tensile strength and yield point of standard malleable iron in general decrease. Standard malleable iron is used in certain applications at temperatures up to 1200 degrees F. Up to that temperature, except under repeated heating malleable iron does not undergo "growth," or permanent increase in volume. Heating standard malleable above approximately 1350 degrees F. results in the redissolving of some of the temper carbon in the iron, with alteration of both the structure and the properties of the metal.

The tensile properties of standard malleable iron, held for short times at temperatures in the range from room temperature to 1200 degrees F., were the subject of an investigation[62] which utilized irons of the following composition:

	Standard Malleable Iron	
	A	*B*
	%	%
Total Carbon	2.30	2.33
Silicon	1.05	0.98
Manganese	0.30	0.34
Sulfur	0.084	0.078
Phosphorus	0.162	0.168

At room temperature, these irons showed the following test results:

	A	*B*
Tensile strength, p.s.i.	55,900	56,600
Yield point, p.s.i.	36,500	35,500
Elongation, per cent in 2"	28.3	19.5
Notched Charpy impact, ft.-lbs.	8.1	6.9
Wedge blows	30	28

The malleable irons tested, it was noted, had the same characteristic curves for tensile properties throughout the temperature range. Tensile strength was observed to drop about 10 per cent when the temperature was raised from room temperature to 212 degrees F., and the strength then increased to substantially its former value when the temperature was raised to 600 degrees F. These changes were not accompanied, however, by a corresponding inverse relationship for ductility; elongation values dropped continuously from room temperature to about 500 degrees F. Above 600 degrees F., while ductility increased at a rapid rate, tensile strength declined at about the same rate until at 1200 degrees F. it was only about 25 per cent of the room temperature figure.

The results of high-temperature testing of such standard malleable irons as are represented by irons A and B, at testing speeds of 0.02-inch per minute to the yield point and 0.2-inch per minute to the tensile strength, gave averages as follows:

	Tensile Strength		*Yield Point*		*Elongation*	
Temp. (°F)	*Average Tensile Strength (p.s.i.)*	*Per Cent Change from Room Temp. Value*	*Average Yield Point (p.s.i.)*	*Per Cent Change from Room Temp. Value*	*Average Elongation (% in 2")*	*Per Cent Change from Room Temp. Value*
75	54,200	0	34,850	0	23.5	0
212	51,200	–6.5	32,850	–6.5	21.1	–10.0
400	52,350	–3.5	32,900	–6.5	14.3	–38.0
600	53,700	–1.5	30,550	–12.0	14.1	–40.0
800	46,500	–15.0	27,650	–20.0	21.8	–8.0
1000	27,750	–52.0	17,400	–50.0	48.5	+105.0
1200	12,550	–77.0	7,700	–78.0	55.5	+140.0

A general high level of rupture stress for standard malleable iron, held at high levels of temperature for long periods of time, is indicated by the results of a study of stress-rupture and elongation properties of the material.[63] In this investigation, test specimens were supplied by four producers, all materials being carefully selected to be representative grades of metal in current production by the malleable iron industry. Chemical analyses of the specimens are shown in Table 5.

TABLE 5

Material		*Si* %	*Mn* %			*Cr*
Low Carbon						
Group A-1	2.26	1.09	0.29	0.074	0.148	
E-1	2.16	1.17	0.38	0.095	0.137	0.017
G-1	2.29	1.01	0.38	0.086	0.11	
High Carbon						
Group B-1	2.50	1.32	0.43	0.159	0.024	0.029

Tests were conducted at 800, 1000, and 1200 degrees F., standard 0.505-inch diameter threaded bars with 2-inch gage length being used. The load was applied to the stress-rupture specimen by means of weights and

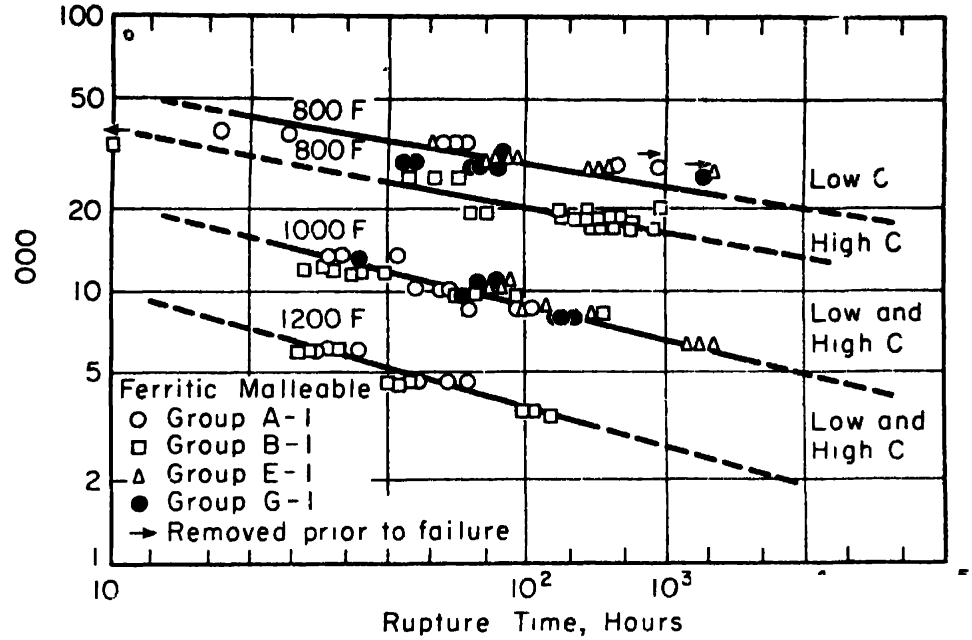


Fig. 26. **Stress-rupture plot for standard malleable iron. On the curve for high-carbon material at 800 degrees F. and on that for 1000 degrees F. points which actually occupy the same stress level have been slightly displaced in order that all data may be shown.**

a lever arm. Creep was measured by means of dial gages calibrated in 0.001-inch which registered movement in the upper portion of the test specimen train.

Stress-rupture plots for low carbon standard malleable irons at 800 degrees F., high-carbon standard malleables at 800, and both high- and low-carbon standard malleable combined at 1000 and 1200 degrees F. are given in Fig. 26. Performance equal or superior to that of other ferritic materials is indicated by these results, particularly at 800 degrees F.; and the strength at 1000 degrees F. is adequate for many applications, strength being retained even at 1200 degrees F. Malleable iron affords usefulness in special applications such as parts for ovens, driers, some types of furnaces, and many kinds of high-temperature fittings, on the basis of these findings.

Typical time-elongation curves for two groups of standard malleable iron are shown in Fig. 27. The three stages of creep generally noted are clearly exhibited in the curves, which emphasize the normally ductile behavior of malleable iron at all times and temperatures investigated. No significant change in either elongation or reduction of area with time was noted in the study. Values obtained for the minimum creep rate—the linear or second-stage portion—varied from 0.0017 per cent per hour for long rupture times to 4 per cent per hour at the highest stress levels and short times. Creep measurements in actuality represent the sum of elongation due to creep and the elongation which might result from growth of the specimen such as might be caused by oxidation. Growth, as was indicated by microstructural examination and measurements on test specimens, is not significant.

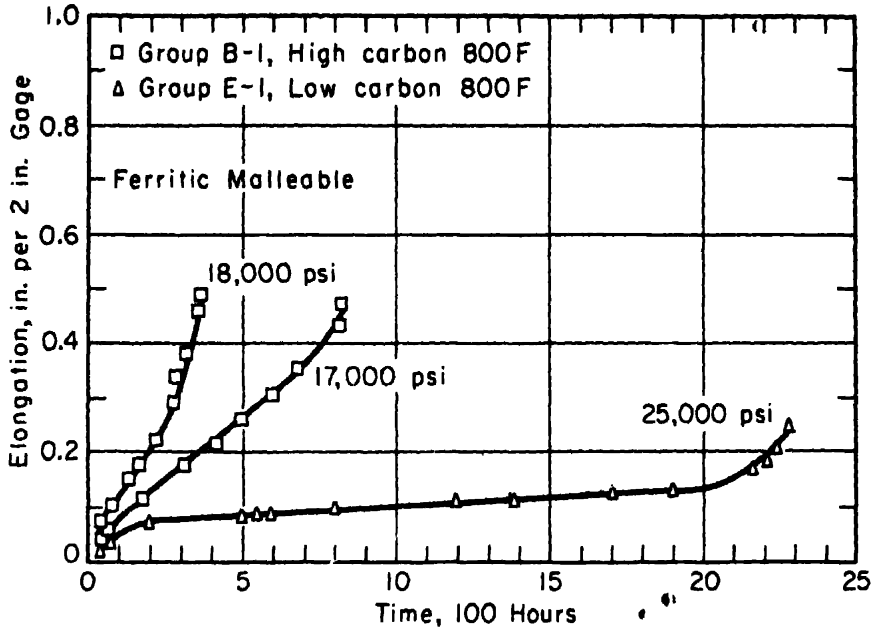


Fig. 27. **Typical time-elongation curves for two groups of standard malleable iron specimens.**

ENGINEERING PROPERTIES

To give effective, economical service in a finished part, a metal must possess, among others, certain characteristics made possible by its physical and mechanical properties. These characteristics, for convenience called the metal's engineering properties, include trueness to final dimensions and shape "as-cast," freedom from stresses, machinability, corrosion resistance, and wear resistance. Since engineering properties such as these have a direct bearing on the finished parts, they are of special importance to the engineer and user. As this section will show, and as Chapter X in discussing machining techniques will further explain, much of the wide use of malleable iron results from its possession of a valuable combination of such characteristics.

Design Versatility

Whenever complexity of design makes fabrication and machining slow and costly, malleable iron castings are efficient and economical. Obviously, coring cavities out of a casting is less expensive than machining them out of a solid structure. Beyond this, however, is the fact that malleable iron can be cast extremely close to finished dimensions, thus reducing finishing costs. Moreover, when a single casting can replace an assembly of numerous parts, a more accurate finished product results, since the accumulation of tolerances due to the assembling of individual components, each carrying its own tolerance, is eliminated. A casting usually is more appealing to the eye than is an assembly of numerous elements.

FREEDOM FROM CASTING STRESSES

Cast metals frequently are subject to internal stresses when the shape of the mold cavity prevents the metal from contracting uniformly throughout during solidification and cooling. These hidden stresses, released or intensified by subsequent machining operations, may produce warpage or distortion of the piece, "casting strains," which may render the casting unfit for use as a finished part. These cannot occur with malleable iron castings, since the annealing operation, which converts white iron into malleable iron, is an integral part of the manufacture, not an optional heat-treatment. It removes any internal stresses which may have been occasioned in the casting process and results in a thoroughly stress-free casting.

MACHINABILITY

Efficiency in the production of finished parts depends to a great degree on the readiness with which machining operations such as turning, drilling, milling, threading, reaming, and so on, are performed, and this in turn depends directly on the machinability of the metal being fabricated. Though it possesses superior toughness and ductility, malleable iron is the most readily machinable and free-cutting of ferrous metals of comparable or higher strength because of its uniformity of structure throughout and because of the nodular form in which the temper carbon exists.

Detailed discussion of the machining of malleable iron, with recommendations based on the best current practice, is deferred to a later chapter in this book, which will discuss machinability in general, analyze speeds and feeds for machining, and present machinability tables and recommended cutting fluids for various machining operations.

COINING

Coining is understood to be a process of either cold or hot forming metals by pressing them to shape or size in a die. It is essentially cold flowing by compression. Some machining operations may be eliminated by coin pressing when malleable is specified because of the ductility of the metal. For this reason, coining is widely used on malleable castings. Available data indicates that, depending on equipment, area, and shape of the surface to be coined, tolerances of ±.010 inches can be readily held. Standard malleable iron, as Fig. 28 shows, can also be punched with ease; punched or cored holes can be drifted to larger size without cracks or fractures.

RESISTANCE TO CORROSION

The wide outdoor use of malleable iron in pole-line hardware, bridge railings and panels, street signs, rail braces and track switch stands, oper-

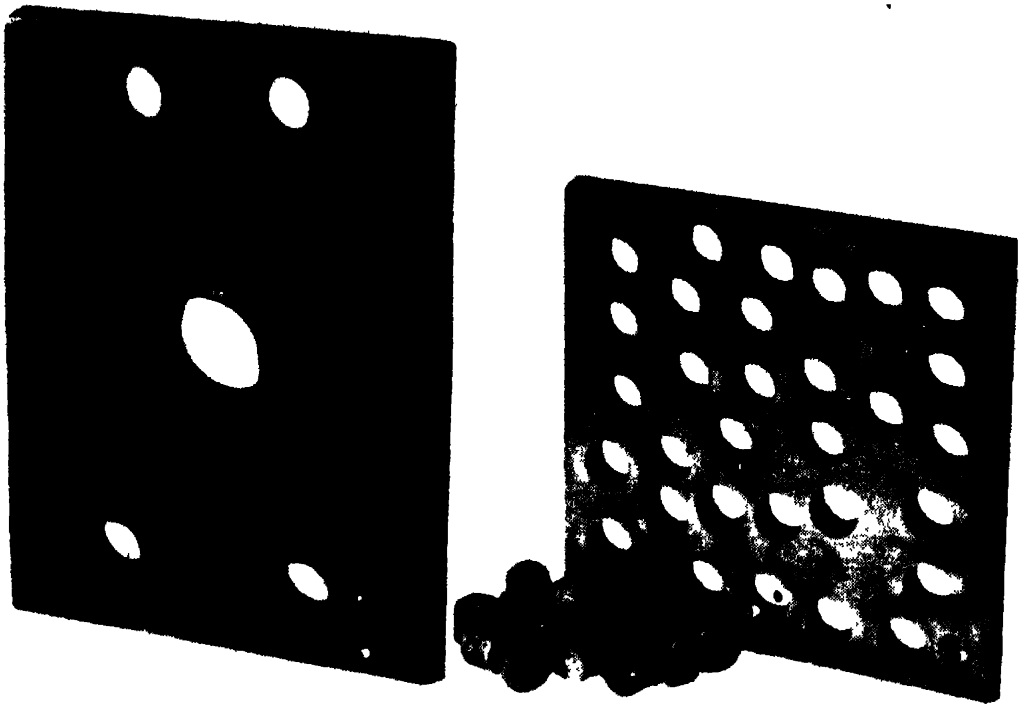


Fig. 28. **Because of its ductility, malleable iron can be punched and sheared like soft steel. On the left, a casting containing five ¾-inch punched holes, the center one drifted to 1½ inches. At right, a casting ⅝-inch thick, with a large number of ¾-inch holes, cold-punched, the distance between holes being sometimes as little as ⅛-inch.**

ating mechanisms of railroad hopper and box cars, and so on, is practical demonstration of the high resistance of the material to atmospheric corrosion.

Effect of Copper on Corrosion Resistance

The addition of copper to the melt in amounts from 0.25 to 0.75 per cent increases the resistance of malleable iron to atmospheric corrosion. In alloy malleable iron, up to 2.00 per cent copper aids in reducing loss due to corrosion by flue gases. The effectiveness of 0.25 per cent copper in reducing corrosion caused by an idustrial city atmosphere is shown in Fig. 29.

Protective Coatings

The many commercial processes for rustproofing ferrous metals may in general be divided into two classes: metallic and non-metallic. The metallic coatings most commonly used are zinc, cadmium, copper, nickel, chromium, lead, tin, and silver. All can be applied electrolytically. However, the most common method of coating with zinc is the hot-dip galvanizing process. Tests have shown that under identical conditions malleable iron takes a heavier iron-zinc alloy layer than does wrought iron or steel.[22]

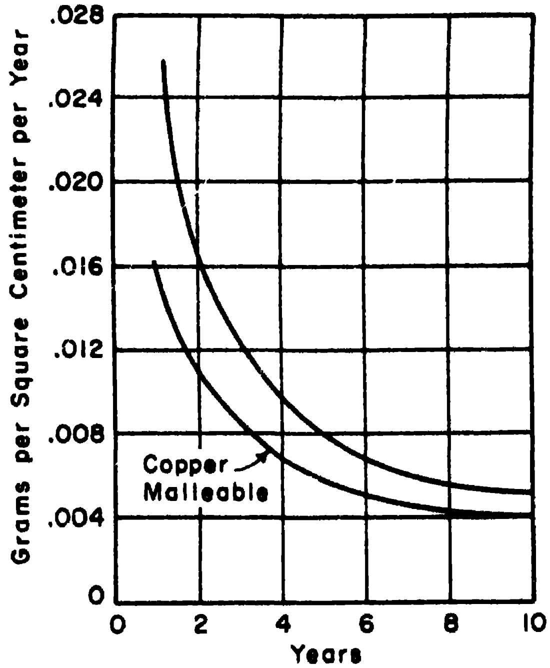


Fig. 29. **Effect of 0.25 per cent copper on the resistance of malleable iron to atmospheric corrosion.**

The importance of careful control of composition, if hot-dip galvanizing is employed, is explained in Chapter XI, "The Metallurgy of Malleable Iron." The type of casting and the use to which it is to be put should determine the kind of coating to be specified. If superior appearance of the finished piece is a prime requirement, electroplating should be employed; with modern techniques, this method provides both excellent appearance and good corrosion resistance.

The two types of non-metallic treatments available and in general use are (1) that which forms a thick skin of iron oxide, and (2) that which forms an iron phosphate coating. Although the iron oxide coating is a protection against rust, it is brittle and will crack if the part is being bent, and so is not suitable for castings subjected to bending or twisting. The iron phosphate coating is flexible enough to avoid the development of cracks but may occasionally have pinholes. For this reason, castings with iron phosphate coating are customarily painted or given an oil or wax treatment, to act as a seal. Castings given the iron oxide treatment may likewise be painted or lacquered. For some service conditions requiring minimum protection a coat of paint will suffice. More severe conditions need more effective protection.

The use of plastic coatings on malleable iron has been very limited in comparison to other types of coatings such as paints, lacquers, and enamels. Industrially, the former have been confined mostly to special applications, which take advantage of their specific properties and where improved performance justifies the higher cost. Since the chief interest probably lies in the purpose for which the coating is used rather than the coating material itself, the more general uses of coatings will be discussed in terms of such purposes as corrosion resistance, insulation, and appearance.

In coating applications most emphasis has been placed on the use of plastics to eliminate degradation by chemical action. Silicone finishes have been found very successful where superior heat resistance or the combination of heat and weather resistance is required. They have been used as protective coatings on hot surfaces of malleable iron parts on boilers, furnaces, stacks, flues, and exhaust manifolds. With aluminum pigmentation, silicone coatings are being used for protection of surfaces subjected to temperatures as high as 1000 degrees F.

Vinyl resins will not adhere to metal surfaces, and until the important post-war development of the "wash" primer system for bonding, only moderate use was made of these resins as coatings. The wash primer system is essentially an alcohol solution of a vinyl butyral resin pigmented with a rust inhibitor such as zinc or lead chromate, which is diluted with phosphoric acid before application. An adherent film is formed by reaction with the metal surface, which is considered to be an inorganic surface conversion coating with an overlying, chemically bonded, organic film. It has been determined that even better corrosion resistance is afforded by use of vinyl coatings over wash primer treatment. Vinyl resins in this combination have found use for protection of malleable iron pipe fittings and structural members against chemical solutions and fumes, for continuous immersion in fresh water, salt water, or sewage, and for underground applications.

The phenolics are known to have excellent water resistance, which has resulted in extensive use of them as protective coatings for underwater applications. They also possess good chemical resistance except against strong alkalies, as well as good abrasion resistance. The resin can be applied in a variety of ways as air-dry varnishes, baked-on films, or on-the-job catalyzed coatings. Although excellent in other respects, the phenolic films have the disadvantage of being very brittle and having poor impact resistance. These disadvantages are not too serious, however, in applications on cast metal parts. As an example, corrosion of malleable iron by fertilizer was eliminated in static tests by a baked-on phenolic coating, and even at deliberately exposed areas under-film creeping of corrosion did not occur

Rust inhibitors, another type of protective coating, are designed to impart additional corrosion resistance to a metal for a short period of time. A broad classification of rust inhibitors is based on the protective film which they form on castings, being either hard, or non-hard drying types. A corrosion inhibiting grease or oil can be applied by dipping or spraying and to be most effective, it must be easy to remove.

WEAR RESISTANCE

In lubricated bearing wear, standard malleable iron like other metals shows excellent performance as long as the bearing pressures are not high enough to break through a lubricating film, and abrasive particles larger than the thickness of the film are not present. Should the film break down, the temper carbon present in malleable iron aids in the lubrication.

To the other types of wear—dry bearing and abrasion—standard malleable iron is not well adapted, because of its soft ferrite matrix. If relative surface speed is high in a dry bearing, galling or welding of the mating parts may occur. Its ferrite matrix likewise makes standard malleable iron unsuitable where bearing parts are subject to the cutting action of hard abrasive particles, such as rough grit, under relatively high speeds and pressures. Good service is provided by hardened pearlitic malleable irons, as will be discussed in later chapters.

WELDING, BRAZING, SOLDERING

Fusion welding of malleable iron, even when very rapidly done, occasions the redissolving of some of the temper carbon in the heated zone. Upon cooling, the redissolved carbon remains in the combined form, so that the structure of the metal in the zone is brittle as compared to the original ferritic structure. Fusion welding of malleable iron consequently cannot be recommended for parts which are highly stressed or subject to impact. There are applications, however, where tensile stresses are low or stresses are compressive only, in which welded malleable irons, even though lower in ductility and impact value at the weld, may be employed. For the arc welding of standard malleable iron, a commercially pure nickel rod or a 10 per cent aluminum bronze rod is to be preferred. The nickel rod affords a good color match with standard malleable iron.

Since the melting range of brazing materials is from 1600 to 1900 degrees F., brazing of standard malleable iron can be accomplished with somewhat less embrittlement than may occur when fusion welding is done, but temperatures must be kept well below 1700 degrees F. The hardness and depth of embrittlement incurred are a function of the length of time spent above the critical temperature of approximately 1350 degrees F. in getting to a brazing temperature and the length of time spent in completing the braze.

Low-temperature solders or the silver solders, which will flow at temperatures under 1350 degrees F., do not affect the mechanical properties of the base iron. They are effective in the sweat-soldering of slip joints in malleable iron. It is important during soldering that the temperature of the casting not exceed 1350 degrees F. In either brazing or soldering, a suitable flux and thorough cleaning with a caustic bath or a vapor degrease are necessary.

HARDENING MALLEABLE IRON

In applications where localized or complete hardening of castings is desirable, pearlitic malleable iron is generally used because of its greater adaptability to the hardening treatment. There are instances, however, in which standard malleable iron, under carefully regulated conditions, is hardened through reconversion of a controlled amount of the temper carbon in the matrix to combined form. The reconversion is accomplished by heating by electric induction, flame, or salt or lead baths, followed by a quench in a suitable medium. In Fig. 30, the hardenesses obtainable by oil quenching are given for one composition as a function of temperature. The holding time is not specified, and the data should be used as a guide only.

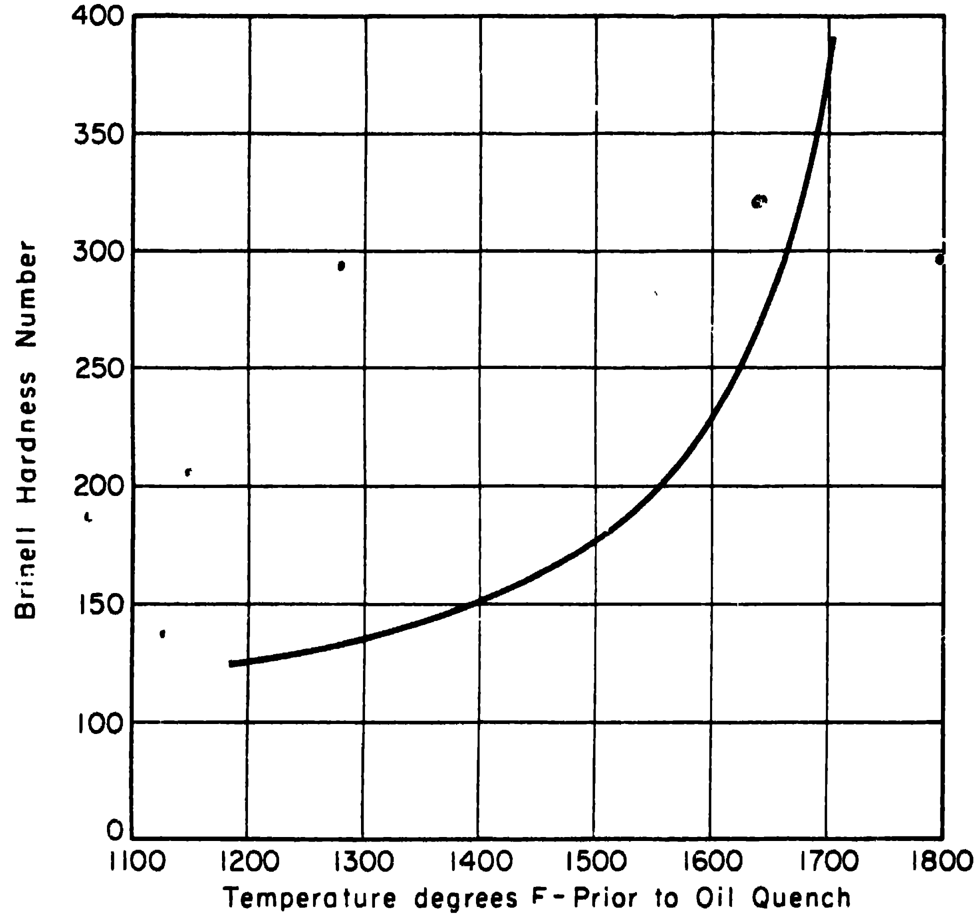


Fig. 30. **Hardness of standard malleable iron resulting from quenching in oil from various temperatures.**

A good example of the use of localized hardening with standard malleable iron is the valve lever shown in Fig. 31. The cam or head end of the lever is hardened to 50-55 Rockwell "C" by immersion of the head in a high-temperature salt bath to a depth of ¾-inch, followed by a water quench. The original toughness of standard malleable iron remains unchanged in the shank and handle of the lever, so that long life of the part even under the most severe use is assured. The high ductility left in the shank is demonstrated by the casting at the left in Fig. 31, which has been bent through 180 degrees.

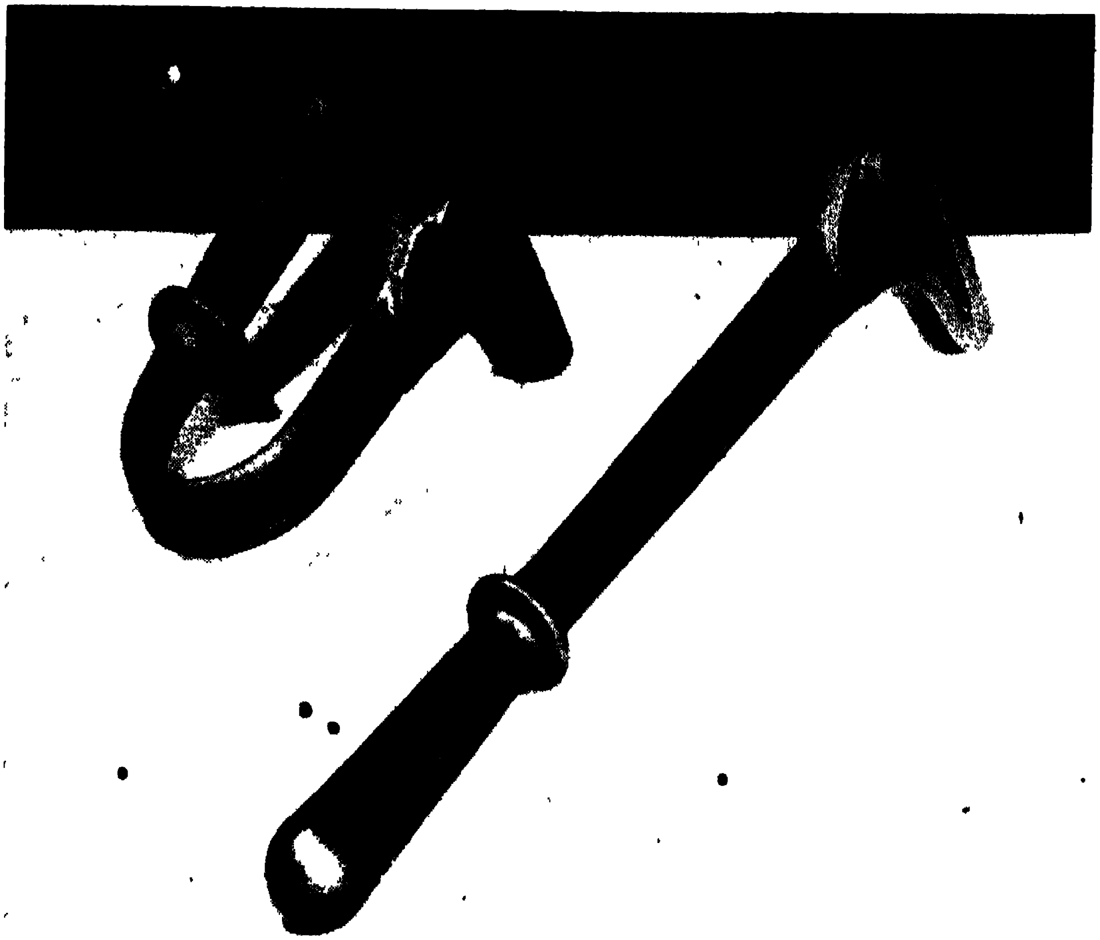


Fig. 31. The cam or head end of the lever has been hardened to 50-55 Rockwell "C." The high ductility remaining in the shank is demonstrated by the casting at the left, which has been bent through 180°.

VI

PEARLITIC MALLEABLE IRON

STRONGER, harder, and more wear-resistant than standard malleable iron, though less ductile and shock-resistant, the pearlitic malleable irons have a high ratio of yield strength to tensile strength, machine easily, and are readily surface- or through-hardened. With such a combination of attributes as these, pearlitic malleable is constantly bringing new tonnage into the foundry. Virtually every major industry today utilizes pearlitic malleable castings extensively for such parts as gears, connecting rods, armament components, chain links and sprockets, Diesel pistons and valve elements, camshafts, crankshafts, and transmission parts, to cite only a few representative examples.

The term "pearlitic malleable iron" or "pearlitic malleable" is applied to that class of malleable iron which, by special processing, is made to contain, in addition to the temper graphite nodules, some 0.3 to 0.9 per cent combined carbon in closely controlled quantity, form, and distribution through the matrix. Because of this structural individuality, first described in 1919 by Professor Enrique Touceda, pearlitic malleable is clearly distinguishable as a definite class from the standard grades of malleable iron, which have no combined carbon in the matrix and hence are called ferritic.

It is to the combined carbon that we may ascribe the characteristic qualities of pearlitic malleable castings, which offer to the designer tensile strengths up to about 125,000 pounds per square inch and yield strengths to over 100,000 p.s.i. Because of its excellent castability, high strength, structural uniformity, rigidity, good properties at elevated temperatures, resistance to fatigue, adaptability to surface- and through-hardening, wear properties, and ease of machinability with excellent machined surface finish, "pearlitic" is being specified for applications of long rigorous service, two examples of which are shown in Fig. 1.

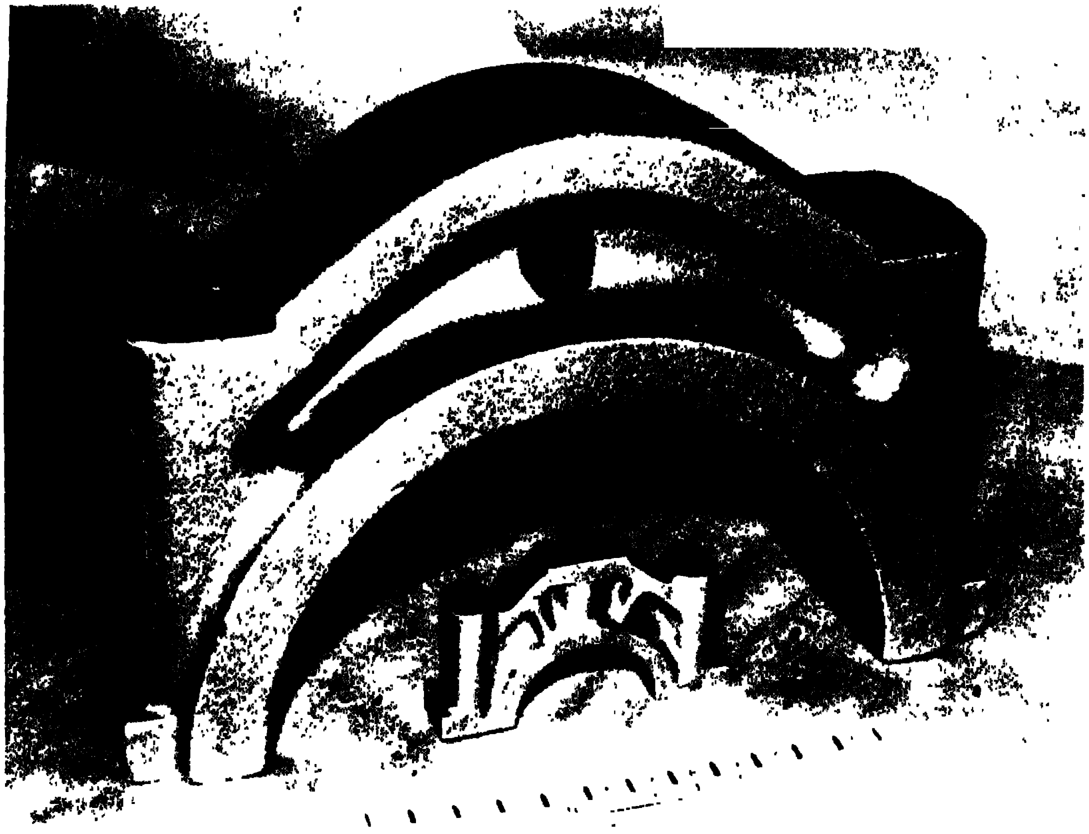


Fig. 1. **A large bearing cap casting for a stationary internal combustion engine. The conventional diesel truck engine crankshaft bearing cap is shown for contrast.**

As with standard malleable iron, the manufacture of pearlitic malleable iron starts with the production of white iron castings in which the carbon is in the combined form. These are basically of the same chemical composition as the white iron castings that are converted into standard malleable by a malleablizing heat-treatment. In the manufacture of one general type of pearlitic malleable iron, however, the metal composition is altered by alloying to facilitate heat-treatment, to improve certain properties, or both. Alloying may be understood to mean only the addition for those purposes of an element not normally present in the composition, or it may be taken as including also the substantial increase, for the same reasons, of the proportion of an element which normally is present in the composition. The second, broader view is followed in this book.

The second step in the pearlitic malleable process—that of heat-treatment—starts out the same as in the production of ferritic or standard malleable castings. In all grades of pearlitic malleable iron, first-stage graphitization is carried to completion. Thereafter the processing departs from the usual malleablizing treatment in one of two ways. In the first of the major methods, the controlled rate of cooling through the eutectoid range is kept rapid enough to retain a desired amount and type of combined carbon in the matrix. Liquid or air quenching and closely regulated furnace cooling are ways employed to obtain this transformation product. The second major method produces pearlitic malleable through the reheat-treatment of fully malleablized castings so as to recombine a desired quantity of carbon and retain it through the matrix. Whatever the method, from approximately 0.3 to 0.9 per cent combined carbon is retained in the matrix of pearlitic malleable castings, the quantity depending upon the properties desired in the particular grade being manufactured. Higher strength and hardness requirements generally necessitate controlled combined carbon in the upper part of the range. In most grades the matrix is later modified by a further treatment which tempers the as-quenched structure, raises its ductility, improves machinability, and increases uniformity. The several basic processes for manufacturing pearlitic malleable irons are described in greater detail in Chapter XI, "The Metallurgy of Malleable Iron."

PHYSICAL PROPERTIES

The retention of part of the carbon in the combined form may produce some slight variations in the physical properties of pearlitic malleable as compared with those of standard malleable iron.

WEIGHT

The *density* of pearlitic malleable iron, formed by the reheat and liquid quench method, lies between 7.20 and 7.35 grams per cubic centimeter, which converts to 0.260 to 0.266 pounds per cubic inch. Pearlitic

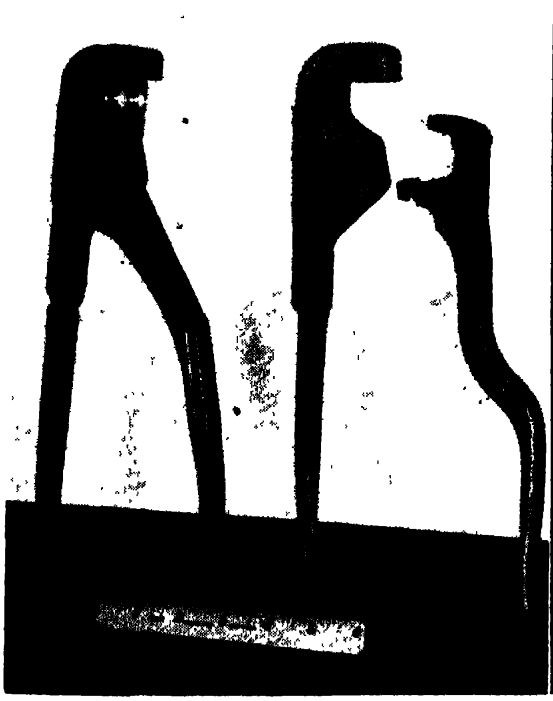


Fig. 2. **A shell molded pearlitic malleable iron crimping tool used in the electrical industry.**

Fig. 3. **A pearlitic malleable iron exhaust valve lever weighing 38 pounds.**

malleable irons made by other methods may show somewhat higher density values, ranging from 7.33 to 7.42 grams per cubic centimeter, or 0.265 to 0.268 pounds per cubic inch.[65] Detailed discussion of the density of malleable iron is to be found in Chapter IV.

The *specific gravity* of pearlitic malleable varies similarly to the density.

VOLUME

The specific volume of pearlitic malleable produced by the reheat and liquid quench method lies between 0.1361 and 0.1389, and that of pearlitic malleable made by other methods between 0.1348 and 0.1364, all these values being ± 0.002.[65]

PATTERN SHRINKAGE ALLOWANCE

The white iron castings converted to pearlitic malleable through heat-treatment shrink approximately ¼-inch per foot during solidification and cooling in the mold. In the subsequent heat-treatment, not all of the combined carbon of these white iron castings appears finally as graphitic or temper carbon. Some combined carbon must be retained in order to impart the properties that are characteristic of pearlitic malleable. Therefore, the expansion resulting from precipitation of the temper carbon during the heat-treatment is not quite so great as that occurring in standard, or ferritic, malleable iron. The actual expansion will usually fall within the range of 0.08 to 0.11 inch per foot and will depend upon the amount of retained carbide, the quenching practice, and the extent of tempering.

Thus the net shrinkage (i.e., solidification contraction, minus heat-treat expansion) will be somewhat higher for pearlitic malleable production than for standard malleable.

THERMAL VALUES

The *specific heat* of the pearlitic malleable irons does not differ notably from that recorded for standard malleable as set out in Table 5, Chapter IV, page 64. Their *coefficient of thermal expansion,* however, is appreciably higher than that of standard malleable, an average figure for one representative pearlitic being 10.9 x 10^{-6} per degree F.[66] Another study utilizing a Bristol dilatometer suggests an average thermal expansion of 7.5-7.6 x 10^{-6} per degree F. on heating from room temperature to 1300 degrees F.[67]

ELECTRICAL AND MAGNETIC PROPERTIES

The combined carbon present in the structure of pearlitic malleable has considerable influence on its electrical and magnetic properties, which differ substantially from those of standard malleable. Pearlitic malleables of 2.5 to 2.6 per cent total carbon and 0.52 to 0.9 per cent manganese give resistivity values of 38.19 to 41.17 microhms per centimeter.[19]

For these irons *coercivity* values ranging between 1.19 and 7.36 oersteds have been reported.[19] The *magnetic permeability*, the ratio of induction to magnetizing force in MKS units, or gausses divided by oersteds, in general increases with greater amounts of combined carbon The permeability of a pearlitic malleable produced by addition of manganese as an alloy was found to be at a maximum, that is, 660, at a magnetizing force of 23.4 ampere turns per inch, or about 12 oersteds. The full magnetizing curve for this iron is shown in Fig. 4.[30]

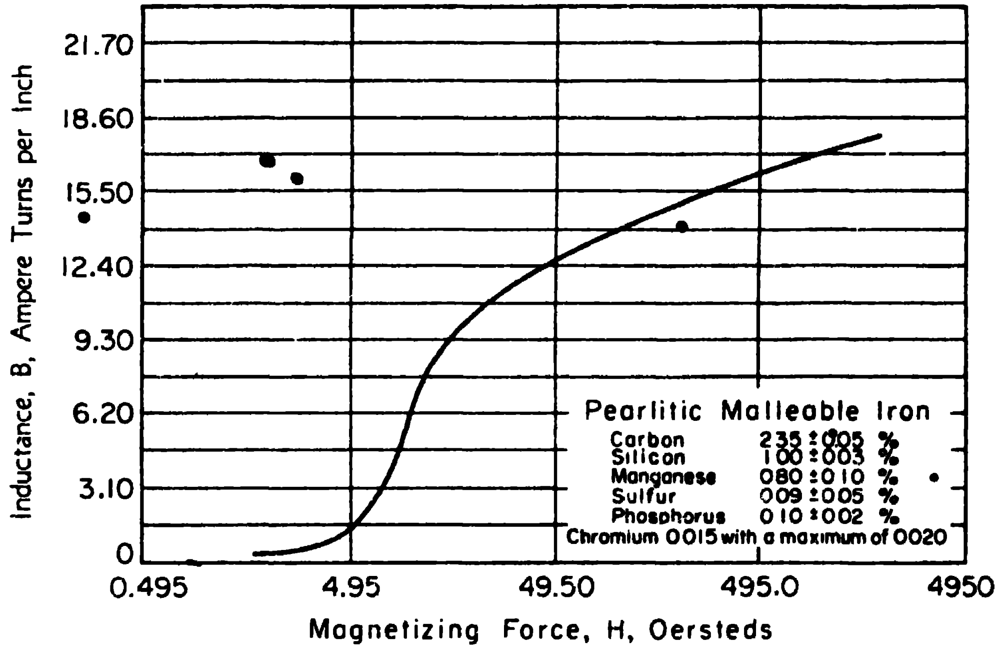


Fig. 4. **Magnetization curve for pearlitic malleable iron.**

MECHANICAL PROPERTIES

The constantly widening range of uses for which pearlitic malleable castings are being specified is a logical result of the desirable mechanical properties which the metal affords, such as excellent tensile values, rigidity, hardness, and wear resistance. A quick comparison of the mechanical properties of the various grades of pearlitic malleable specified by the American Society for Testing Materials and other agencies with those of standard malleable is to be found in Table 2 of Chapter III, page 52. The present chapter will discuss the properties of pearlitic malleable in greater detail.

PROPERTIES IN TENSION

Pearlitic malleable irons are available over a wide range of tensile properties. Generally, the high-strength grades have relatively low ductility, and the high-ductility grade possess intermediate strength properties. Tensile strengths of 65,000 to 120,000 p.s.i. and yield strengths of 45,000 to 100,000 p.s.i. with elongations of 16 to 2 per cent in 2 inches, are obtainable in the various grades regularly produced by the industry, as shown in Table 1, which lists minimum tensile requirements for seven grades of pearlitic malleable iron specified by the American Society for Testing Materials.

TABLE 1. TENSILE PROPERTIES OF PEARLITIC MALLEABLE IRON (REQUIREMENTS OF A.S.T.M. SPECIFICATION A 220-55T)

Grade	*Minimum Tensile Strength (p.s.i.)*	*Minimum Yield Point or Yield Strength (p.s.i.)*	*Minimum Elongation (Per Cent in 2 inches)*
45010	65,000	45,000	10
45007	68,000	45,000	7
48004	70,000	48,000	4
50007	75,000	50,000	7
53004	80,000	53,000	4
60003	80,000	60,000	3
80002	100,000	80,000	2

Since pearlitic malleable may not exhibit a definite yield point on the stress-strain curve, the yield strength is the term generally specified. It is taken at either an offset of 0.2 per cent or an extension under load of 0.5 per cent. The yield strengths of pearlitic malleable irons are compared graphically with specified values for other ferrous and non-ferrous metals in Fig. 5.

The ratio of yield strength to tensile strength is 0.65 to 0.9, the ratio for high tensile-strength irons being in the upper part of this range. The modulus of elasticity of representative pearlitic malleable irons is 25,500,000 p.s.i. to 28,000,000 p.s.i.[68,69,70,71]

EFFECT OF MACHINING TEST BARS ON TENSILE VALUES

Small are the differences in tensile values that may appear when the results obtained with machined pearlitic malleable test bars are compared with those from bars tested as cast to the standard 5/8-inch diameter. A number of studies have confirmed this. In one,[72] the comparisons were made on a series of pearlitic malleable irons whose properties extended over a wide range—75,000-130,000 p.s.i. tensile strength and 55,000-110,000 p.s.i. yield strength. The tensile strength values of the machined bars were from 4 to 6 per cent higher than those of the unmachined bars, the greater difference being at the upper strength levels. The differences in yield strength fell from 5 per cent in low-strength pearlitic malleables to 3 per cent in the highest strength grades. No significant difference was found in elongation values.

In a second investigation,[73] sets of 24 bars 5/8-inch in diameter were

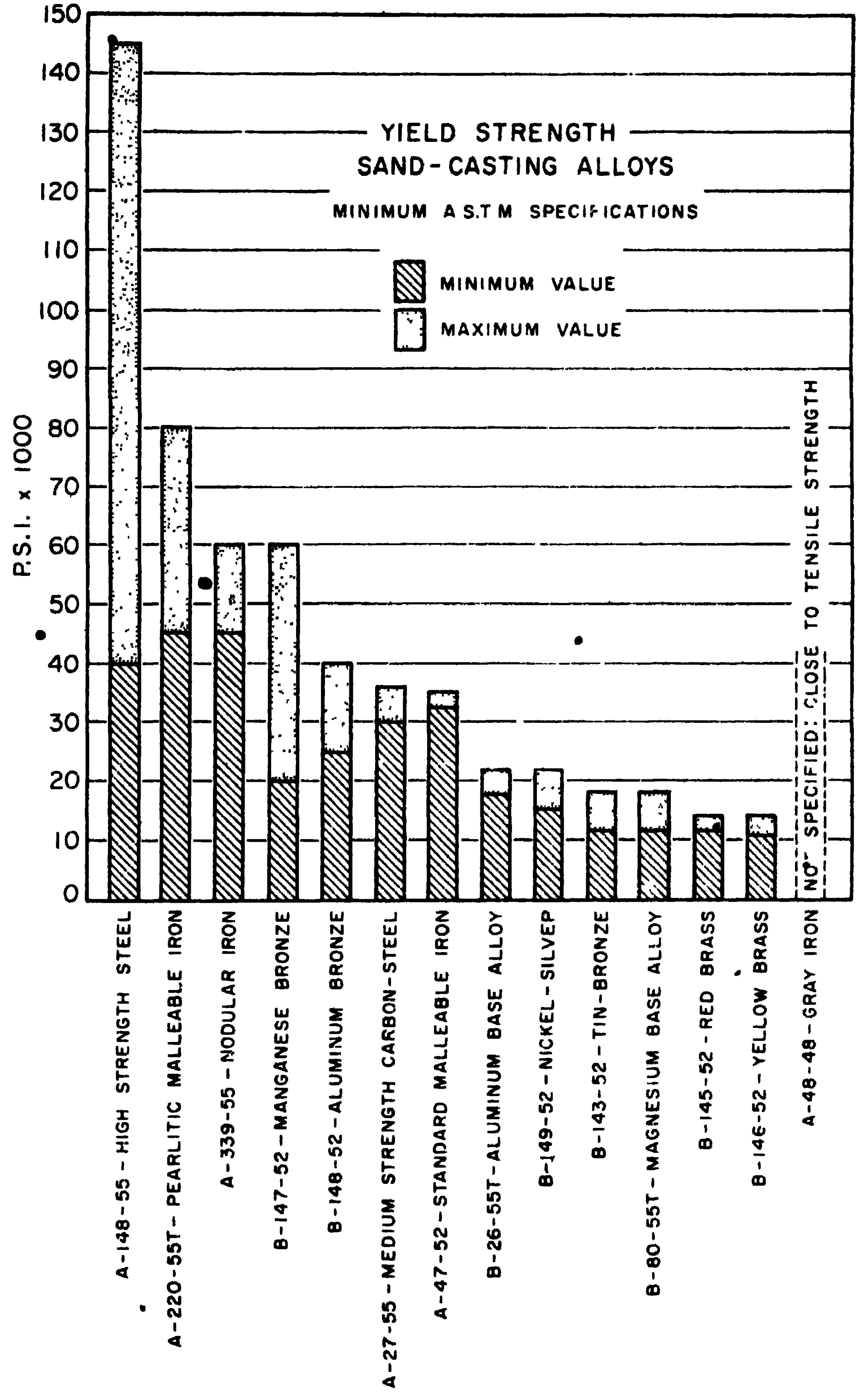


Fig. 5. **Yield strength of pearlitic malleable iron and various other cast metals.**

cast from two successive production air furnace heats. After prescribed heat-treatment, the metal properties complied with A.S.T.M. grades 45010, 45007, 48004, 50007, and usually 53004. Half of the bars were machined down to ½-inch in diameter; then all bars were tested in tension. The properties of the unmachined bars averaged 83,380 p.s.i. tensile strength, 53,750 p.s.i. yield strength, 14.75 per cent elongation in 2 inches, and 197 Brinell hardness number. The test results of the machined bars averaged 3.6 per cent higher tensile strength, 1.8 per cent higher yield strength, and 0.35 per cent lower elongation in 2 inches. Thus the discrepancy was even less than that indicated by the above research.

Employing sub-size specimens (0.375-inch diameter, 1.5-inch gage length) with threaded grips, and machined from the gage length portion of standard 5/8-inch diameter cast-to-size bars, a third investigation[74] was conducted, using duplexed pearlitic malleable irons of grades 48004, 60003, and 80002. The test results were compared with values obtained from regular unmachined 5/8-inch diameter bars poured from the same ladle. The unmachined bars tended to show higher tensile and yield strengths by 7.5 and 6.9 per cent, respectively. The machined bars averaged 0.5 per cent higher elongation in 2 inches.

From the results of these three studies it is clear that the differences in tensile values that may occur between machined and unmachined test bars are not great, usually amounting to less than 5 per cent. The direction and magnitude of these small differences seem to depend more on the method of manufacture than on any other specific factor. The tests indicate the uniformity of properties throughout the cross-section of pearlitic malleable irons. For routine control purposes, the values obtained from standard unmachined bars give a reasonably accurate measure of the properties of the metal.

Correlation of Test Bar Results with Properties of Castings

From time to time tensile specimens have been machined from pearlitic malleable castings and the test results compared with those secured from separately cast test bars. Close correlations are generally found. Frequently the differences will run as low as 3 or 4 per cent.

In one rather extensive study[74] of this kind, a total of 96 specimens were machined from sets of four different commercial castings, two to six bars being taken from each of the castings depending on its size and geometry. Each of the four kinds of castings was produced in three different grades of pearlitic malleable iron by the appropriate heat-treatment of unalloyed duplexed iron. The greatest average difference in any of the tensile values between bars machined from the castings and those separately cast to size was under 20 per cent. This is appreciably better correlation between test bar and casting properties than is attainable in many other cast metals, where property discrepancies as high as 75 per cent have been reported between castings and corresponding separately cast test bars. The study substantiates the fact that the separately cast-to-size malleable tensile bar adequately represents the properties that may be expected in pearlitic malleable castings, without the necessity for pouring heavy, ideally-fed blocks from which test specimens must be machined at appreciable cost and which may give deceptive results.

EFFECT OF COMPOSITION ON PROPERTIES

Detailed discussion of the influence of the chemistry of white iron upon the properties of pearlitic malleable produced from it is presented in Chapter XI, "The Metallurgy of Malleable Iron." This section therefore will be confined to the summarizing of general principles and of a number of relevant findings reported in the literature.

Total carbon is kept on the low side of the range in the production of pearlitic malleable iron in the higher elongation grades. Silicon favors both primary and secondary graphitization.

Manganese is an important component of malleable iron and is included in amounts found in practice to be sufficient to balance the sulfur. An increased amount of manganese is used by some producers to retard graphitization and to achieve other desired results.[75] When not adequately balanced with manganese, the carbides in pearlitic malleable are strongly stabilized by sulfur.

HARDNESS

Selection of the grade of pearlitic malleable to be used in a particular application may be determined by the hardness required in service. Since pearlitic malleable castings are used in so many components subject to frictional wear and abrasion, such as gears and rocker arms, for example, the great range of hardness available in the material is of marked importance. Brinell hardness numbers common to the A.S.T.M. grades of pearlitic malleable iron range from 163 to 269 as shown in Table 2. In addition, surface or through-hardening is obtainable with a heating and quenching treatment, as is explained later in this chapter.

TABLE 2. TYPICAL BRINELL HARDNESS NUMBER RANGE OF A.S.T.M. GRADES OF PEARLITIC MALLEABLE IRON

A.S.T.M. Grade	*Typical BHN Range*
45010	163-207
45007	163-217
48004	163-228
50007	179-228
53004	197-241
60003	197-255
80002	241-269

In instances where the sample is too small to be tested by the Brinell method or where the large impression of the Brinell indenter might be objectionable on a finished surface, the Rockwell hardness tester may be used to advantage. Figure 12 of Chapter V, page 87, illustrates the corre-

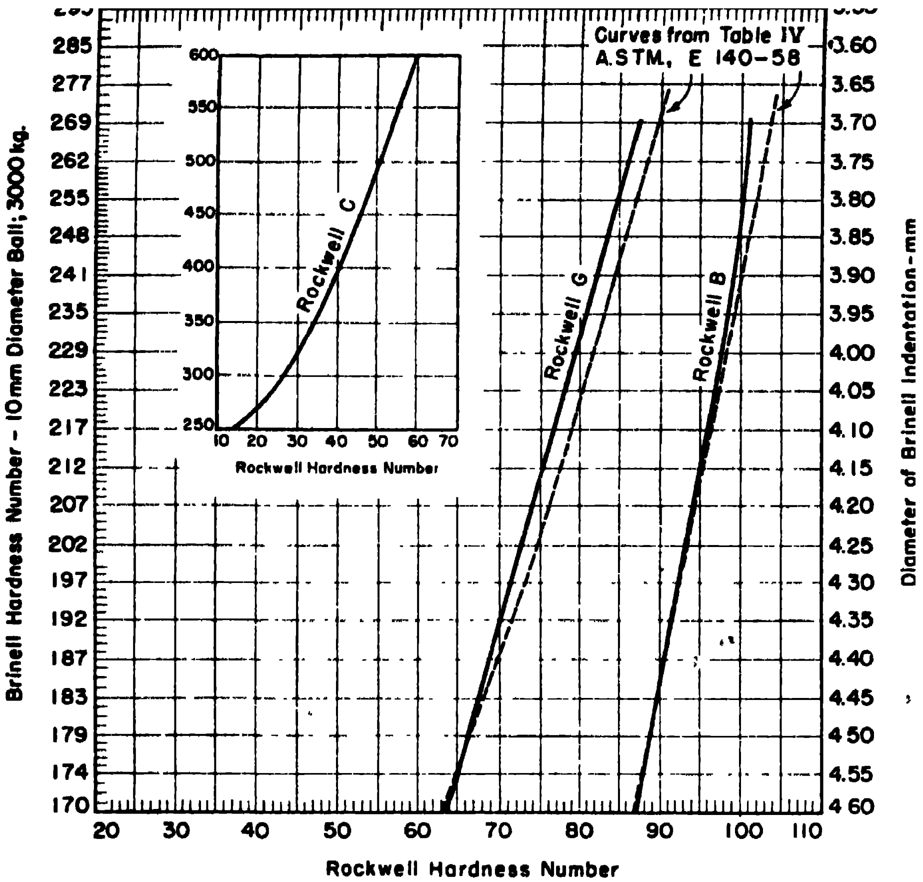


Fig. 6. **Chart for conversion from Brinell to Rockwell *B* and *G* scales for pearlitic malleable iron.**

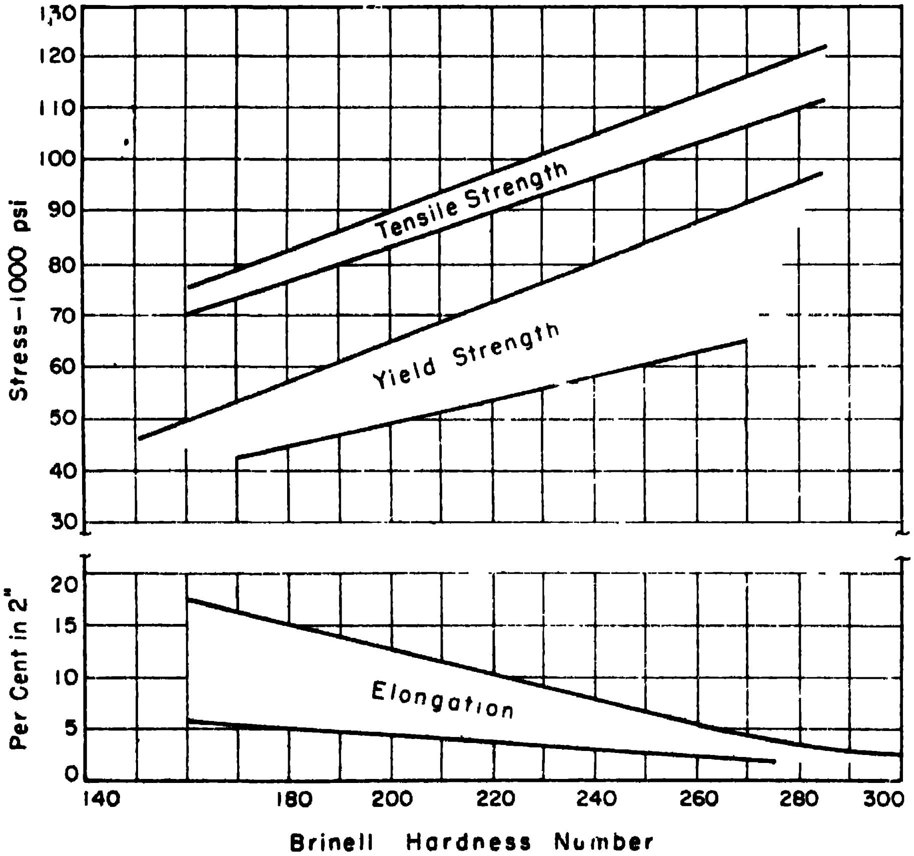


Fig. 7. **Relation of hardness and tensile values of pearlitic malleable iron.**

lation for standard malleable irons between Brinell hardness numbers and two Rockwell scales. Similarly, Fig. 6 shows this relationship for pearlitic malleable iron. It is apparent that the Rockwell B and G scales may be employed satisfactorily for the ranges of hardness common to most pearlitic malleable irons. When the Rockwell method is used, it is imperative that the surface be properly prepared, and it is desirable to take multiple readings at each location to be tested.

Generally, the tensile and yield strengths are higher and the ductility is lower when the hardness of pearlitic malleable is raised. This relationship is shown graphically in Fig. 7. It is further illustrated by the bar

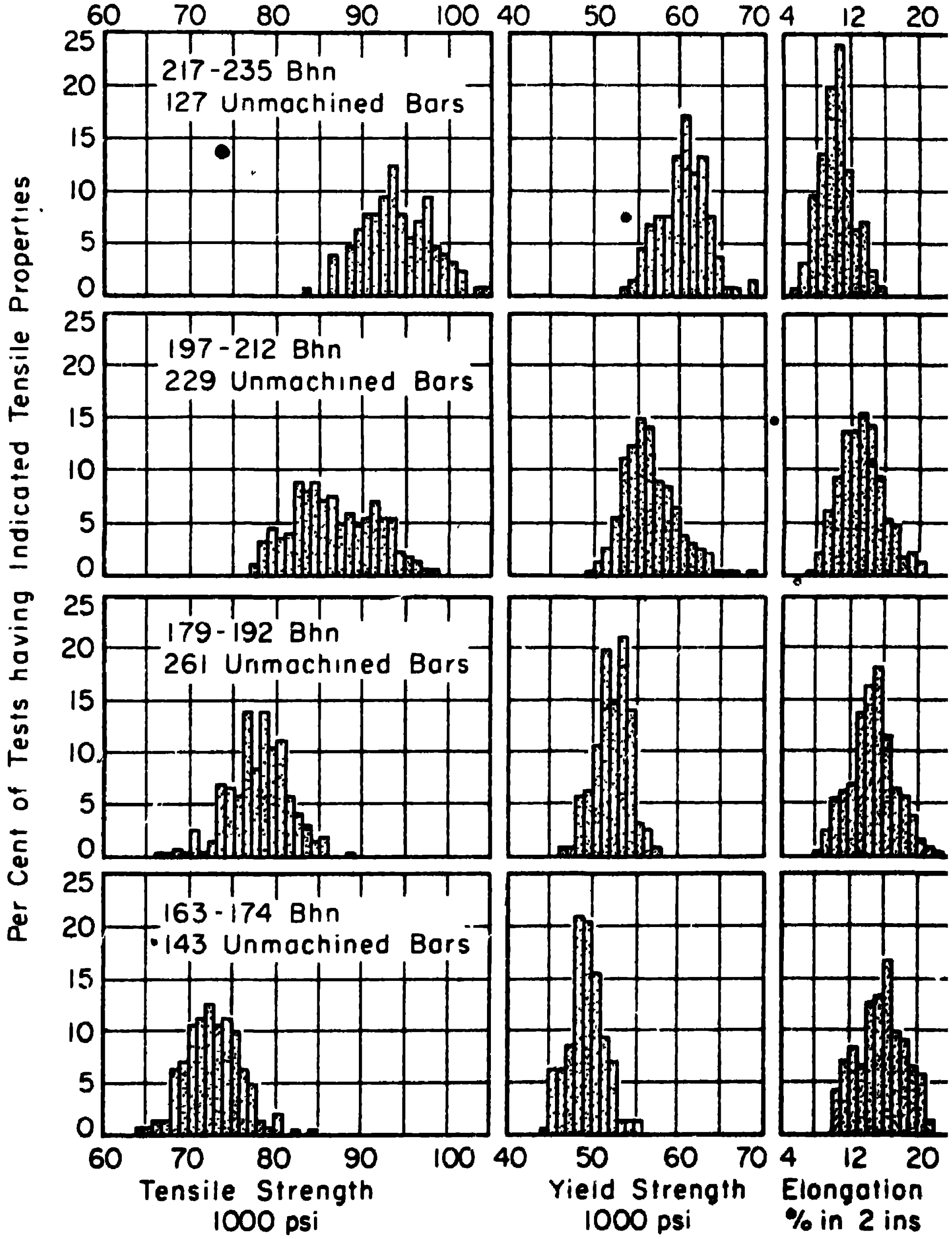


Fig. 8. **Frequency distribution of tensile properties at various hardness levels for unmachined alloyed pearlitic malleable iron from commercial heats.**

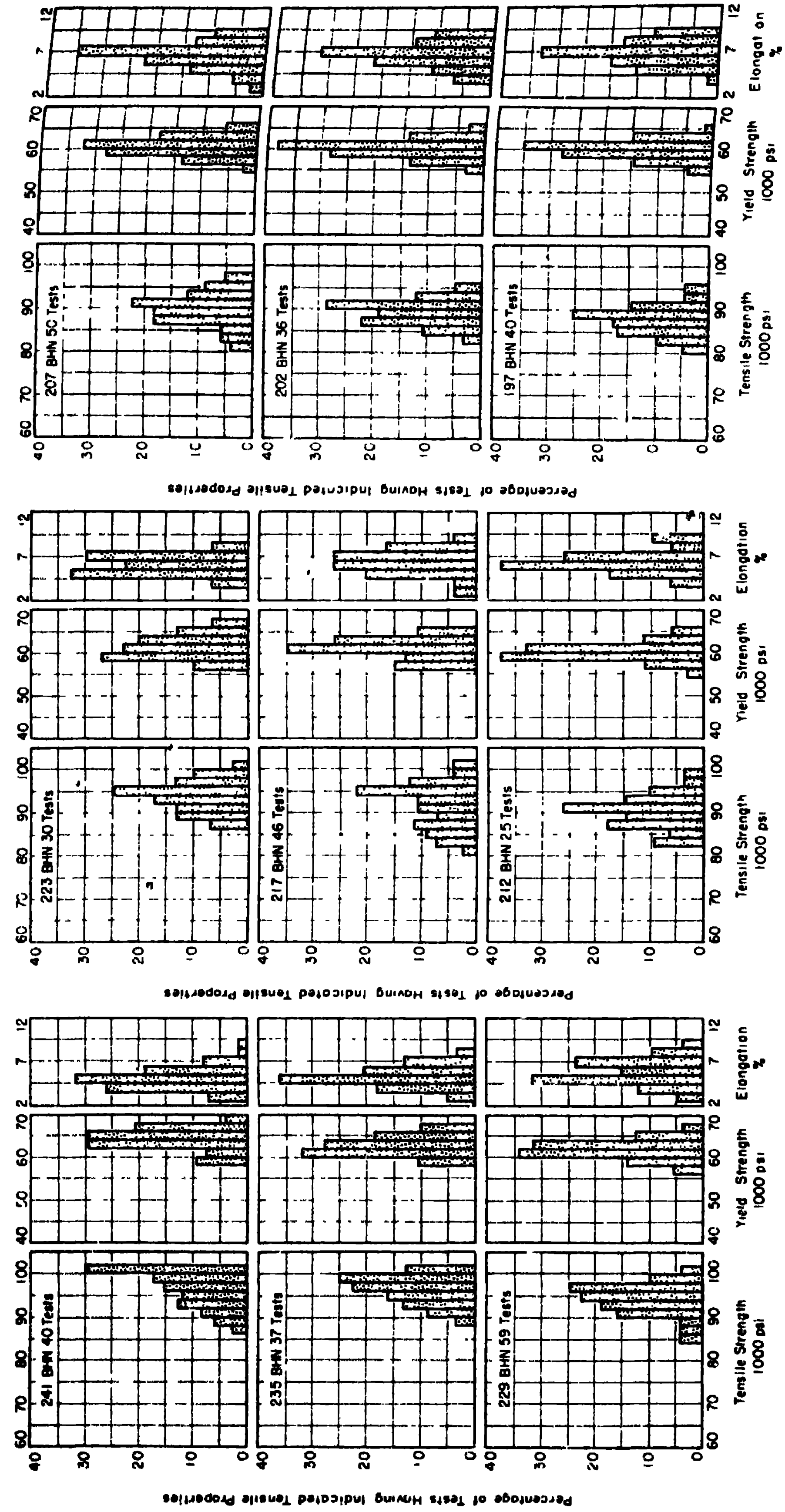


Fig. 9. **Frequency distribution of tensile properties at various hardness levels for unmachined pearlitic malleable iron from commercial heats.**

graphs of Figs. 8 and 9, which depict the frequency distribution of tensile properties of unmachined bars at various hardness levels for daily heats of commercially produced pearlitic malleable iron. The data for Fig. 8 are based on standard tensile test bars made by batch-melting, alloying, air-quenching, and sub-eutectoid tempering. Fig. 9 presents similar data from another producer for unalloyed pearlitic malleable.

The hardness of pearlitic malleable castings increases with their combined carbon content. This is illustrated by Fig. 10 in which is plotted the combined carbon vs. Brinell hardness for one type of pearlitic malleable that was air-quenched from 1680 degrees F. and tested.

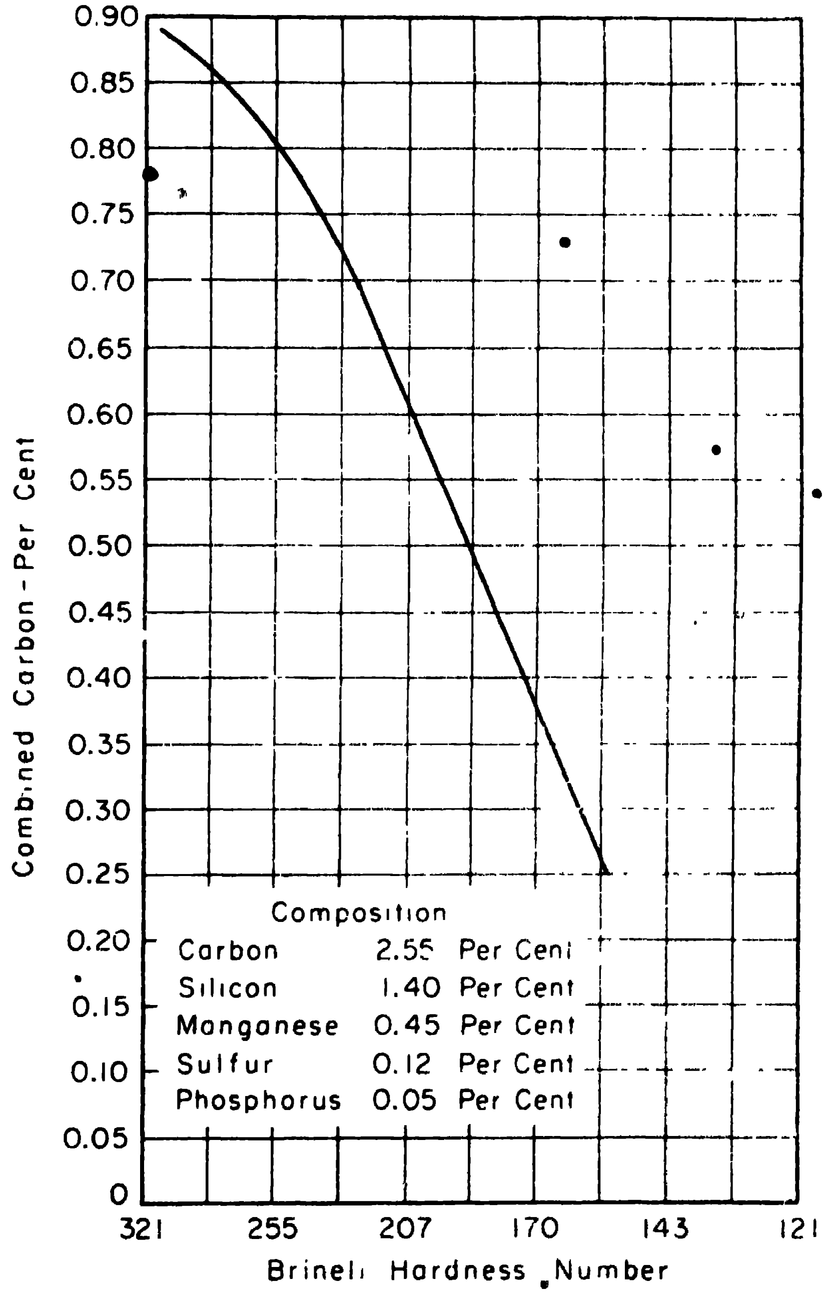


Fig. 10. **Relationship between combined carbon content and Brinell hardness of one type of pearlitic malleable iron.**

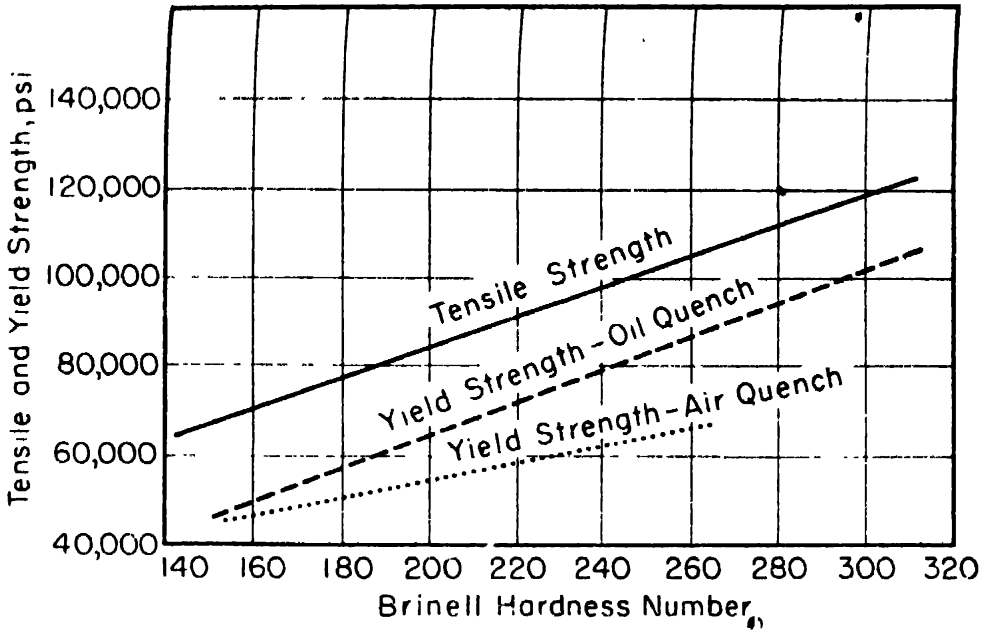


Fig. 11. Relationship between hardness and the tensile and yield strengths of manganese-alloyed pearlitic malleable iron.[70]

The hardness is related to tensile and yield strength as shown in Fig. 11. It will be seen that tensile strength is unaffected by quenching medium; however, quenching medium does influence the yield strength, particularly at higher hardness levels.

FATIGUE PROPERTIES

The general discussion of the fatigue properties of standard malleable irons in Chapter V, page 88, applies to pearlitic malleables. However, because of the higher static strengths of the latter, higher fatigue strengths would be expected. We find this to be the case.

In one study,[71] fifty-five unnotched fatigue specimens were machined from standard tensile test bars cast from the same ladle of duplexed white iron, which was converted into three sets of pearlitic malleable iron of approximately the same hardness by three different heat treatments. The fatigue specimens were run at 7,000 cpm. on a Krouse rotating beam testing machine.[285] The dimensions of the specimens, the heat treatments given the three sets, and the resulting stress-cycles (S-N) curves are shown in Fig. 12. It may been seen that the median fatigue limit for this high-strength duplexed pearlitic malleable iron is approximately 40,000 psi. at ten millon cycles. Since the static tensile strengths of the three sets of specimens averaged around 100,000 psi., the fatigue ratio for the material is about 0.40.

Employing grade 50007 pearlitic malleable and 0.300-inch diameter rotating beam specimens, another investigation[76] developed the curves presented in Fig. 13. The ten million cycle fatigue limit was found to be 37,000 psi. for unnotched specimens and 30,000 psi. for specimens having

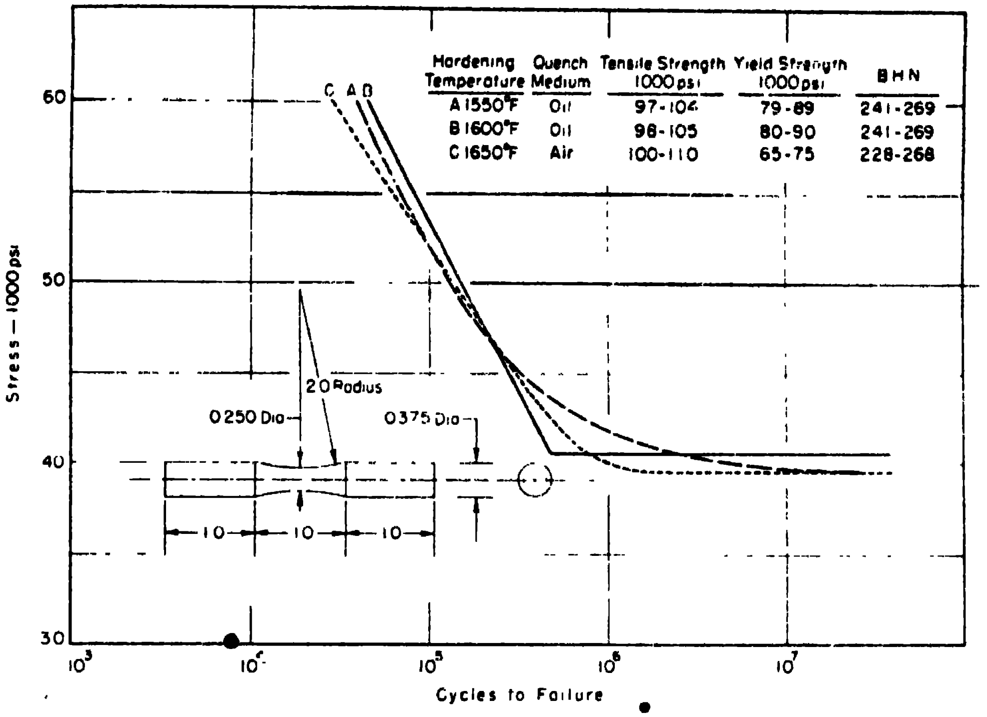


Fig. 12. **S-N curves for unnotched pearlitic malleable irons, using a Krouse rotating beam testing machine.**

a 60-degree V-notch, 0.050-inch deep with a 0.060-inch radius at the base of the notch. With static tensile strengths in the range 75,000 to 78,000 psi., the fatigue ratio is 0.48-0.50 for this pearlitic malleable. At 10^7 cycles it may be seen that the fatigue strength reduction factor, or fatigue notch factor, K_f, is 37,000/30,000, or 1.2. This indicates that pearlitic malleable of this kind is not as notch-sensitive as many other materials, representa-

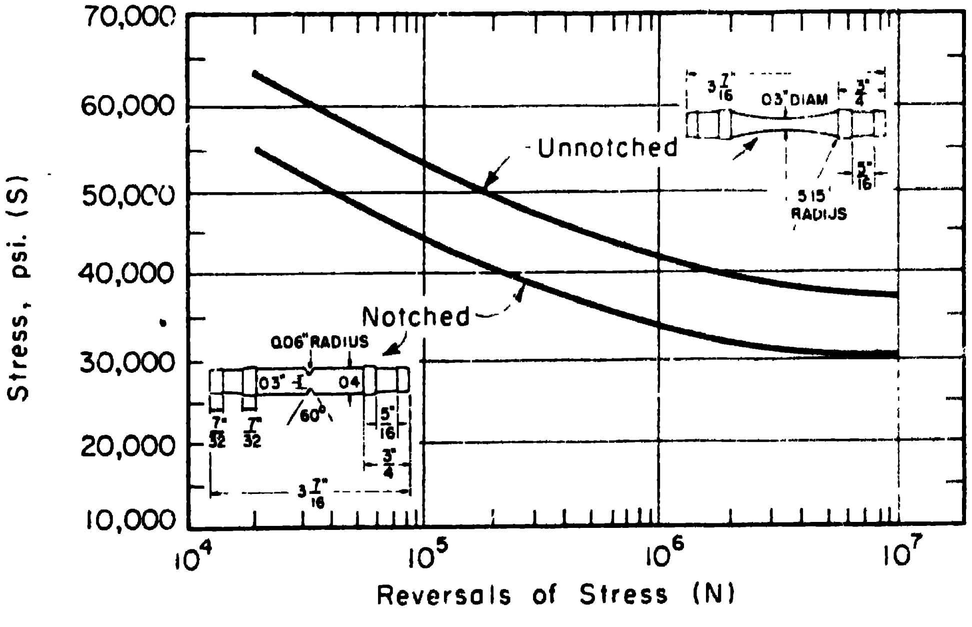


Fig. 13. **Fatigue limit of unnotched and notched test specimens of Grade 50007 pearlitic malleable iron.**

TABLE 3. FATIGUE NOTCH FACTORS (K_t) FOR SOME MATERIALS

Material	*Static Tensile Strength (p.s.i.)*	*Section Diam. (in.)*	*Notch Angle (Degrees)*	*Notch Root Radius (in.)*	*Fatigue Limit* (p.s.i.)*		*K_t, Fatigue Notch Factor*
					Unnotched	*Notched*	
Pearlitic Malleable Iron. 50007[76]	78,000	0.300	60	0.060	37,000	30,000	1.23
Gray Cast Iron. class 40[267]	42,600	....	..	....	23,300	19,000	1.26
Nodular Cast Iron. 60-45-10[286]	68,500	0.417	45	0.010	28,000	16,800	1.67
Steel. wrought. A.I.S.I. 1035[290]	88,000	....	..	....	35,000	19,000	1.45
					to	to	to
					39,000	27,000	1.84
Steel, bar. A.I.S.I. 4130[77]	.....	—semicircular groove—			68,500	37,000	1.85
Steel. rolled bar. A.I.S.I. 5140[280]	141,000	0.270	60	0.025	78,000	42,000	1.85
Aluminum. extruded. 24S-T4[291]	80,300	0.250	60	0.010	29,500	12,500	2.36
Steel. bar stock. A.I.S.I. 2330[287]	129,000	0.250	60	0.010	80,000	32,000	2.50
Steel. wrought. A.I.S.I. 1045[289]	97,000		45		49,000	18,000	2.35
	to	0.300	&	0.010	to	to	to
	120,000		60		67,000	27,000	2.72

* Rotating beam test at 10,000,000 cycles.

tive values for which have been listed in Table 3. In other words, in pearlitic malleable there is a good factor of safety against notch fatigue failure.

To evaluate the fatigue properties of pearlitic malleable iron in reversed torsion, research was conducted at the University of Illinois.[71] The specimens were a duplexed, high-strength, oil-quenched and tempered, pearlitic malleable iron having a test section 0.250-inch in diameter and 7/8-inch long. These were machined out of 1-inch diameter by 6-inch long bars. Testing was carried out at a constant amplitude of torsional deflection, operating at 1730 cycles per minute. Seven of the specimens that did not fail after ten million cycles were rerun at higher stress levels to obtain additional finite life data. As shown by Fig. 14, the median fatigue limit for this pearlitic malleable in reversed torsion was 32,650 psi. The standard deviation was 3,250 psi., and 95 per cent of all specimens would be expected to survive 10,000,000 cycles at 30,300 psi.

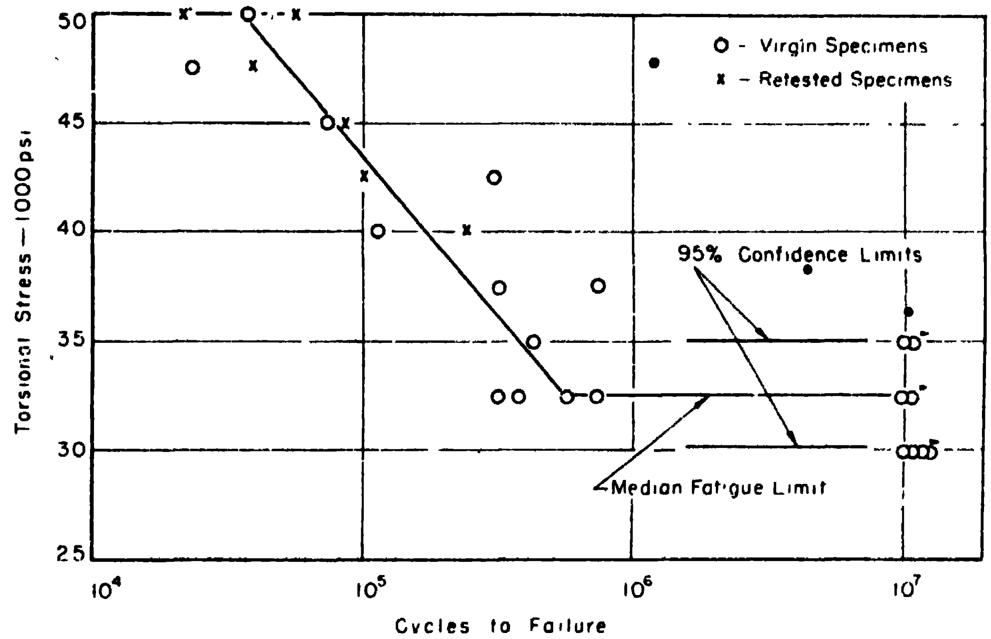


Fig. 14. **S-N curve for torsional fatigue loading of pearlitic malleable iron. Ninety-five per cent confidence limits are shown.**

Prior to accepting pearlitic malleable iron as a replacement for forged A.I.S.I. 1046 steel crankshafts, one leading automobile manufacturer ran dynamometer tests on the two materials and obtained comparable fatigue properties.[78] Notched impact fatigue tests were also run on specimens machined from the counterweights of the pearlitic malleable crankshaft. The angle of the notch was varied from 10 to 30 degrees. No effect of variations in notch sharpness could be discerned from the fatigue test results.

The fatigue life of pearlitic malleable iron is extended manyfold by adequate shot peening in critical locations. The degree of this improvement depends upon the type of fatigue loading, the design of the casting, and the efficiency of the shot peening operation. Maximum benefits are obtained if particular attention is given to those surfaces that are to be subjected to the greatest tensile stresses. In one series of tests,[52] the life of pearlitic malleable specimens increased some 50 times under the peening conditions and test methods that were employed. These results are plotted in Fig. 15.

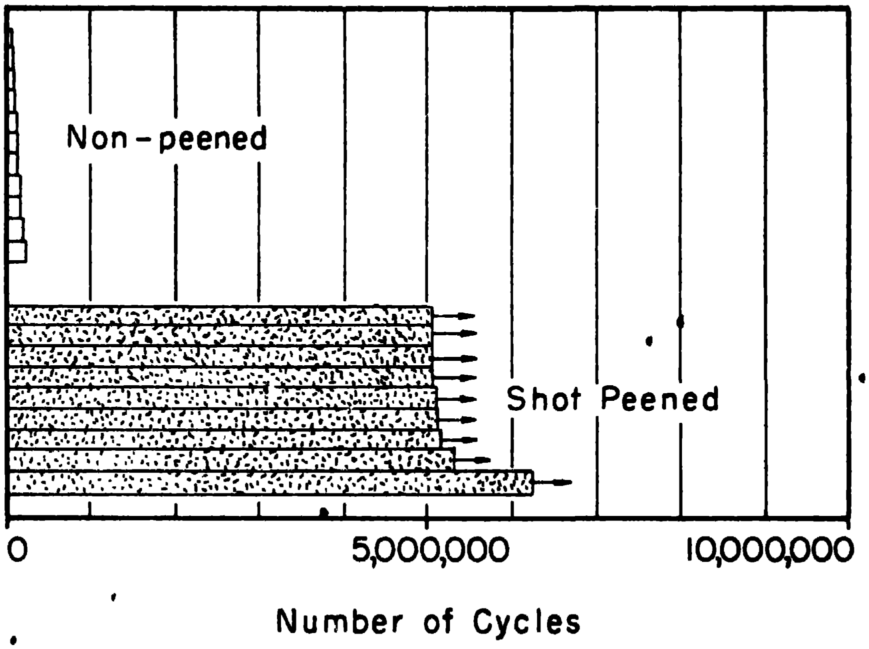


Fig. 15. **Effect of shot peening on fatigue life of pearlitic malleable irons.**

Damping Capacity

The specific damping capacity (the ratio of the energy lost in one vibration cycle to the total energy of that cycle, expressed as a percentage) of pearlitic malleable irons has been determined[54] from one set of specimens made by air-cooling and tempering to Brinell hardness of 223 and two other sets oil-quenched and tempered to Brinell hardness of 212 and 255, respectively. All three materials gave almost identical results.

With increasing stress levels from 5,000 p.s.i. to 35,000 p.s.i. the specific damping capacity was found to rise from approximately 1.9 per cent to 5.3 per cent. Thus pearlitic malleable would be expected to damp out vibrations somewhat better than Grade B cast steels and nodular cast irons, but not quite so well as standard malleable.

Shear Strength

Shear strength determinations were made on a series of pearlitic malleable irons that ranged in tensile strength to over 125,000 p.s.i.[55] Values for shear strength from 65,700 p.s.i. to 102,550 p.s.i. were obtained. The shear strengths thus fell within 70 to 85 per cent of the tensile strengths. Another investigator[76] has reported a value of 60,000 p.s.i. for shear strength of one particular grade of pearlitic malleable with a tensile strength of 78,000 p.s.i.

TORSIONAL PROPERTIES

From tests run in accordance with A.S.T.M. Method A 260-47 to determine the torsional properties of pearlitic malleable irons and using multiple samples of all the grades, the modulus of rupture was found to be approximately equal to the tensile strength of the material. The modulus of elasticity in torsion was found to be unaffected by the grade of pearlitic malleable, averaging 9,970,000 p.s.i. (range 8,790,000 p.s.i. to 10,710,000 p.s.i.). The yield strengths in torsion ranged from 24,500 p.s.i. to 82,300 p.s.i., and varied inversely with the angle of twist, viz. 363 degrees to 69 degrees. In hardened material the upper limit of yield strength in torsion is greater. The relationship of torsional properties to hardness is summarized in Fig. 16, in which the curves are based on average values. Representative torsion bars showing a high degree of twist and resulting factor of safety appear in Fig. 17.[50] By suitable hardening treatments the yield strength in torsion may be raised to as high as 110,000 p.s.i. for a pearlitic malleable hardened to R_c 40.

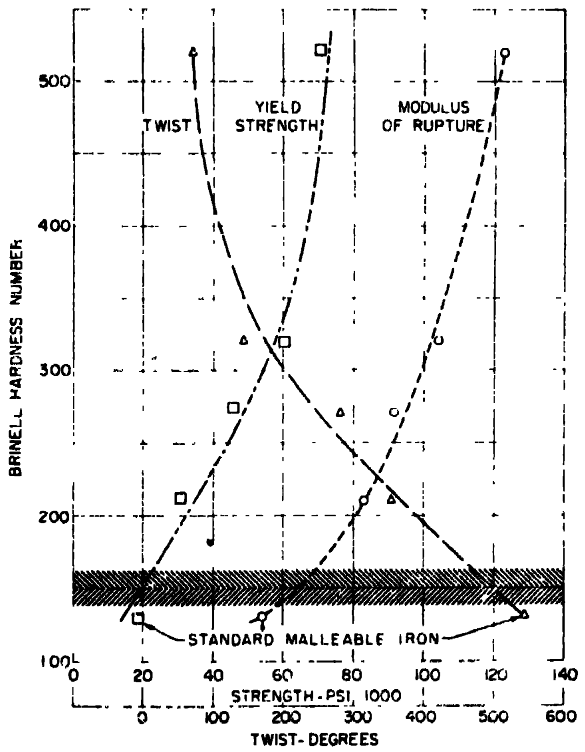


Fig. 16. **Torsional properties of pearlitic malleable iron in relation to hardness. Note that even at the high hardness levels excellent torsional properties are exhibited.**

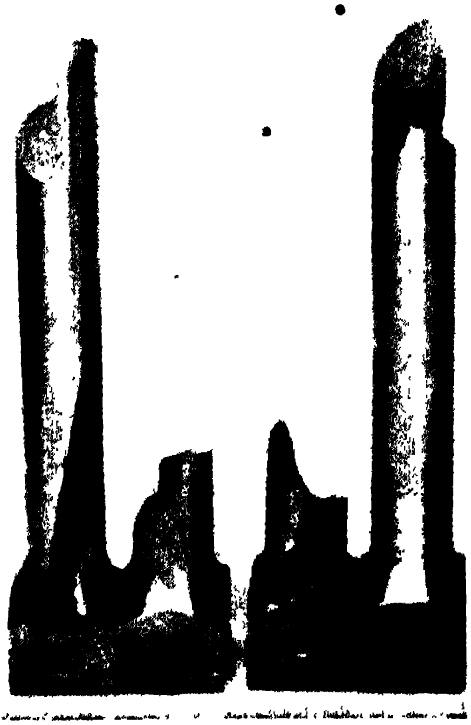


Fig. 17. **These high strength pearlitic malleable iron torsion test specimens all show a high degree of twist.**

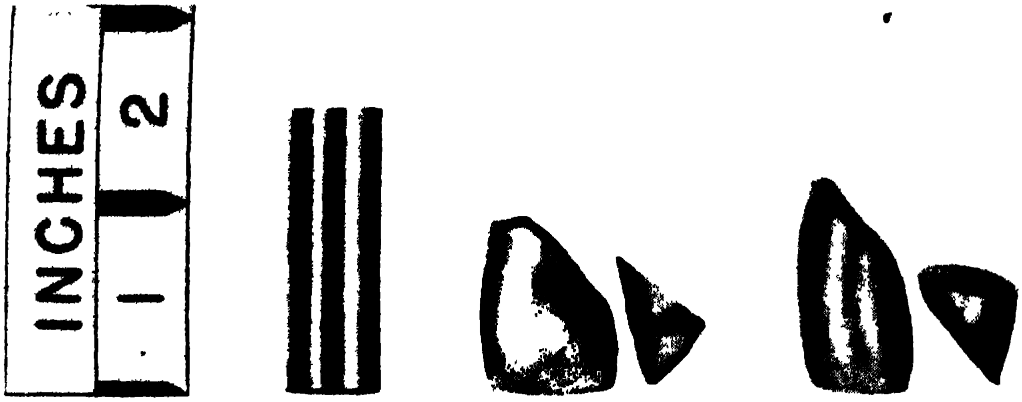


Fig. 18. **Pearlitic malleable iron compression bars before and after testing, illustrating a range of compressive strength from 197,000 to 290,000 psi.**

PROPERTIES IN COMPRESSION

The compressive yield strength is approximately equal to the yield strength in tension for pearlitic malleable irons. Both the compressive strength and the modulus of elasticity in compression are independent of other properties. The compressive strength ranges from 197,000 to 290,000 p.s.i., for specimens ranging in hardness from 180 to 340 BHN. Compressive strength may be increased by supplementary heat treatment. The modulus of elasticity in compression runs 23,200,000 p.s.i.[56] Pearlitic malleable iron compression bars after test are shown in Fig. 18.

IMPACT PROPERTIES

There is no universally accepted test for evaluating the impact resistance of all materials. Test results are affected by the method of shock loading, the presence or absence of stress-raisers and their geometries, the size and shape of the test specimen, and the temperature. A number of different procedures have been employed for evaluating impact properties; the two principal ones are discussed in Chapter V. Some of the results obtained by these methods with pearlitic irons are summarized below.

Cantilevered, unnotched specimens of two pearlitic malleable materials, one made by batch melting, the other by duplexing, the bars being 0.505-inch in diameter, were tested at room temperature, and showed the following average values.[55]

Static Tensile Properties

Tensile Strength (p.s.i.)	*Yield Strength (p.s.i.)*	*Elongation (per cent in 2 inches)*	*Brinell Hardness Number*	*Impact Strength (ft. lbs.)*
69,500	47,100	11.0	163	68.3
81,100	54,650	13.0	183	82.7

Cantilevered, notched specimens, 0.525-inch in diameter with a notch 0.010-inch deep with 0.010-inch radius at the base, of pearlitic malleable irons, made by alloying with manganese and special heat-treatment, tested at 76 degrees F., showed the following average properties:[55]

Static Tensile Properties

Tensile Strength (p.s.i.)	*Yield Strength (p.s.i.)*	*Elongation (per cent in 2 inches)*	*Brinell Hardness Number*	*Impact Strength (ft. lbs.)*
87,300	54,900	9.5	201	24.0
100,000	72,000	5.5	235	10.5
106,600	94,600	3.5	277	10.0
123,600	113,500	2.0	315	8.5

Charpy V-notched bars of spheroidized pearlitic malleable iron gave maximum values up to about 14 foot-pounds.[46] While this may seem to be a relatively low-energy value, the material exhibited tough or ductile-type characteristics when subjected to shock loading. Only by a sufficient lowering of the temperature did a brittle-type fracture develop, and this when the impact values had dropped to about 4 or 5 foot-pounds. Charpy unnotched tests on both air-cooled and oil-quenched pearlitic malleable specimens gave impact values of 22 to 35 foot-pounds.[79]

Tensile impact tests carried out with specimens conforming to Type V, Fig. 9 of A.S.T.M. E 23-47T (Appendix), and performed at temperatures of about 76 degrees F., gave the following average properties:[53]

Static Tensile Properties					
Tensile Strength (p.s.i.)	*Yield Strength (p.s.i.)*	*Elongation (per cent in 2 inches)*	*Brinell Hardness*	*Tensile Impact Strength (ft. lbs.)*	*Tensile Impact Elongation (% in 2 inches)*
85,000	56,400	15.0	204	84.3	15.7
86,700	56,900	8.0	207	62.2	8.8
90,100	64,700	9.0	212	67.3	9.0
106,400	90,400	4.5	277	31.0	2.4
123,100	111,500	2.5	311	19.5	0.2

EFFECT OF TEMPERATURE ON MECHANICAL PROPERTIES

As with all materials, the properties of pearlitic malleable iron are responsive to changes in temperature and at very high or very low temperatures may be quite different from those at room temperature. Elevated temperatures affect the properties of pearlitic malleable iron about as they do those of standard malleable, except for differences in magnitude of the test values, which can be considered due to the presence of combined carbon in the pearlitic malleables and to the way in which their microconstituents are distributed.

TENSILE PROPERTIES (STATIC)

Determination of the tensile properties of pearlitic malleable iron in one study[92] used specimens of the following composition:

Iron	*Total Carbon* %	*Silicon* %	*Manganese* %	*Sulfur* %	*Phosphorus* %
P	2.33	0.98	0.64	0.078	0.168
E	2.27	1.22	0.48	0.17	0.11
F	2.23	0.96	0.81	0.09	0.15
H	2.23	1.14	0.64	0.08	0.11

The following room temperature tensile values were exhibited:

Iron	*Tensile Strength (p.s.i.)*	*Yield Strength (p.s.i.)*	*Elongation (Per cent in 2 inches)*
P	75,400	42,000	10.0
E	92,900	57,300	8.5
F*	90,100	44,800	18.0
H†	90,200	49,400	12.5

* Single test only reported for this iron.

† Machined bar used in tests. All other irons tested unmachined.

Mechanical properties of these irons, in tension at elevated temperatures, were obtained by use of an electric furnace which surrounded the specimen and was so designed that the temperature gradient along the machined 2-inch gage length of the specimen could be held within ± 3 degrees F. throughout the test. The specimens were brought to the desired temperature and then stressed to failure at that temperature. In this study, the several types of pearlitic malleable were reported to have high strength combined with considerable ductility over the temperature range from 30 to 600 degrees F. Above 600 degrees F., strength declined and ductility increased.

Using duplexed pearlitic malleable iron made by air-quenching and tempering, P. C. Rosenthal[80] of the University of Wisconsin ran short-time (15-20 minutes) exposure tests. In Fig. 19 these results are presented together with those of the study discussed above.[93]

Studies of the effect of long-time high-temperature exposure conducted for this handbook[93] utilized two groups of low-carbon pearlitic malleable irons, of the following composition:

	Carbon %	*Silicon* %	*Manganese* %	*Sulfur* %	*Phosphorus* %	*Chromium* %
Group E-2	2.27	1.15	0.89	0.098	0.135	0.019
Group G-2	2.29	1.01	0.75	0.086	0.11	....

The specimens were from different suppliers, were produced by arrested first-stage graphitization following a small manganese ladle addition, and

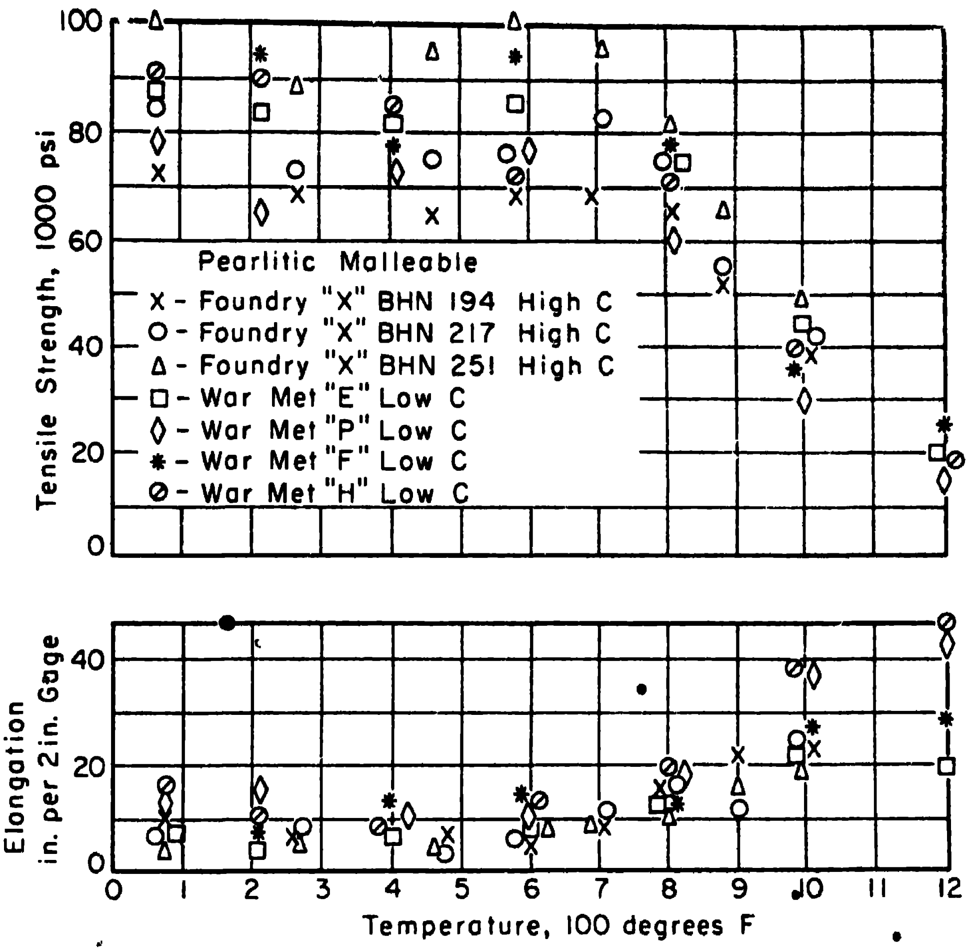


Fig. 19. **Tensile properties of pearlitic malleable iron held for 15-20 minutes at elevated temperatures.**

met the tensile requirements of the first five grades of pearlitic malleable in A.S.T.M. Specification A 220-55T. Findings, presented in Fig. 20, showed performance superior to that of ferritic malleable at 1000 degrees F., but slightly inferior to that of high-carbon ferritic malleable iron at 800 degrees F.

A number of points obtained with pearlitic malleable at 800 degrees F. are plotted in Fig. 20. The curve through these points, a least-squares fit by standard methods, indicated a minimum performance superior but very similar to that of low-carbon ferritic material at the same temperature. In fact, there appeared reason to believe that these particular low-carbon pearlitic malleable irons exhibit unusual characteristics at 800 degrees F., quite similar to those shown by the ferritic malleables discussed in Chapter V. This can be demonstrated quite clearly on a Larson-Miller plot, where the points at 800 degrees F. show a marked deviation, just as in the case of ferritic malleable shown in Fig. 26 of that chapter, page 105. From this it was concluded that this low-carbon pearlitic malleable acts as a different material at 800 degrees F.

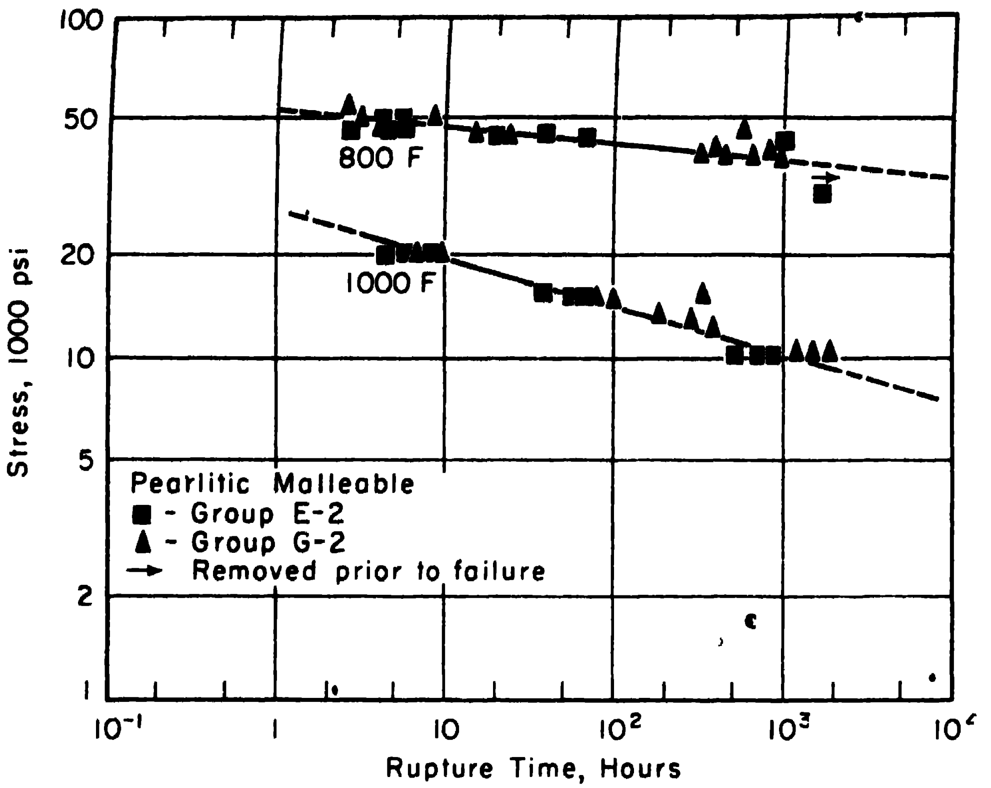


Fig. 20. **Stress-rupture plot for pearlitic malleable irons at 800 and 1000 degrees F.**

The values obtained for these pearlitic malleable irons compare very favorably with those reported[81] in another investigation of the effect of long-time high-temperature exposure on the hardness and tensile properties of both alloyed and unalloyed pearlitic malleable irons. The base iron for the test specimens was duplex-melted and contained 2.6 per cent total carbon and 1.4 per cent silicon. The room-temperature properties of the pearlitic malleable specimens were 90-92,000 p.s.i. tensile strength, 60-72,000 p.s.i. yield strength, 4 per cent elongation in 2 inches, and 229 Brinell hardness number. When this iron was heated to 1000 degrees F., held for one hour at temperature, and tested, the tensile and yield strengths of the unalloyed pearlitic malleable had dropped to 46-47 per cent of their room-temperature values; elongation had increased to 14 per cent in 2 inches, or some 350 per cent over room-temperature values. At temperatures of 1100 and 1200 degrees F. and at longer exposure times, the effect was even more marked. However, the metal alloyed with 0.3 per cent or more molybdenum showed much better stability at elevated temperatures even after 1,000 hours exposure. The comparison is made in Fig. 21.[81] This alloy served to stabilize the pearlitic matrix and to strengthen the structure.

While in some pearlitic malleable irons there may be some small decline in tensile strength at temperatures up to about 300 degrees F., it may be generally concluded that normal room temperature tensile strengths will prevail up to 700 degrees F., above which strengths fall off and ductility rises. Nevertheless, pearlitic malleable irons retain more strength at elevated temperatures than do many other cast metals. For example, at 800 degrees F. pearlitic malleable will still have approximately 85 per cent of its room-temperature tensile properties, whereas some other cast metals would have negligible strength.

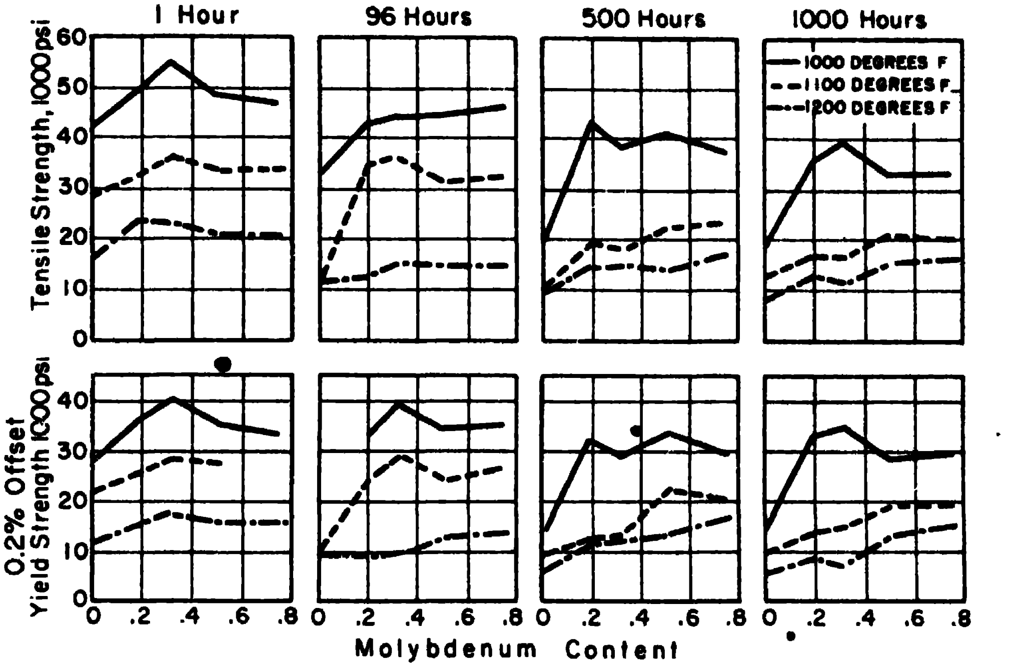


Fig. 21. **Relationship between molybdenum content and the tensile and yield strengths of pearlitic malleable iron for different periods at elevated temperature.**

Stress—Time to Rupture

Rupture of structural materials under stress at room temperature occurs by plastic yielding and eventual tensile and compression failure. At elevated temperatures, however, the phenomenon of creep, which is continued deformation under constant stress, often leads to failure. The creep behavior of two groups of pearlitic malleable iron specimens at 1000 degrees F., in a study carried out for this handbook,[63] is shown in Fig. 22. The same type of curve was obtained at all temperatures investigated. Approximately half of the elongation takes place in the first two stages of creep, which frequently account for the useful life of a part in service. This portion of the elongation generally occurs in about 70 per cent of the time to failure, this time value varying from approximately 60 per cent at higher loads and temperatures to somewhat over 80 per cent for longer time tests.

Figure 23 represents the results obtained in another study from an oil-quenched and tempered pearlitic malleable iron of grade 80002 at 800 degrees F.[82] The data show stresses of about 32,500 p.s.i. for rupture in 100 hours and 25,000 p.s.i. in 1,000 hours.

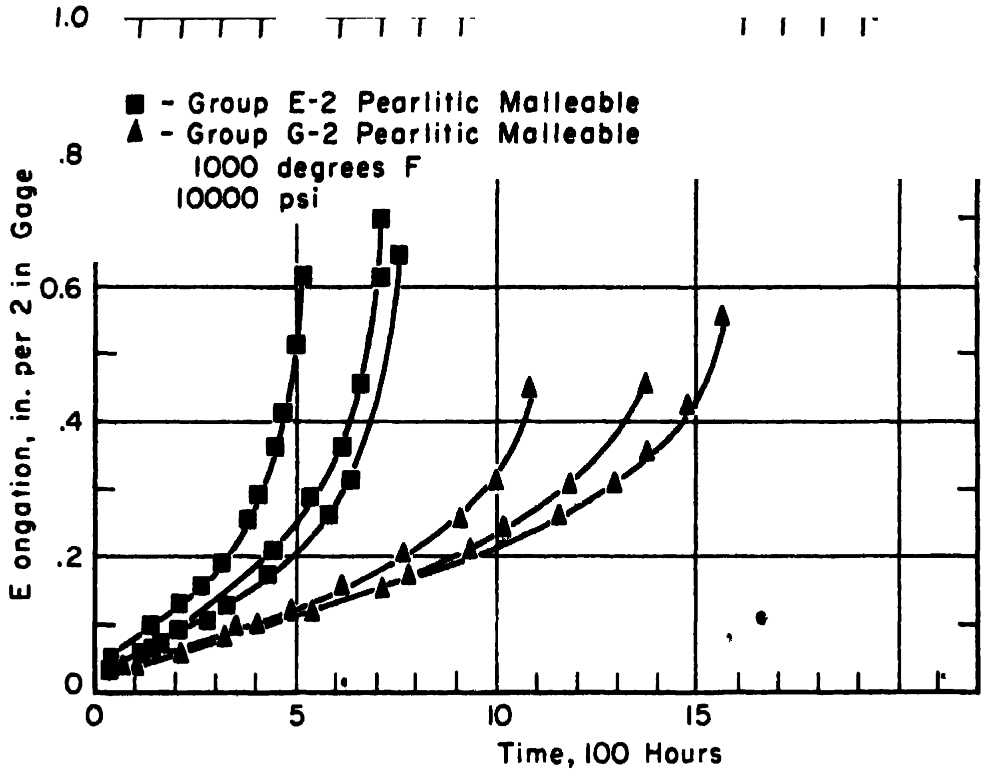


Fig. 22. **Time-elongation curves for two groups of pearlitic malleable iron at 1000 degrees F. and 10,000 psi.**

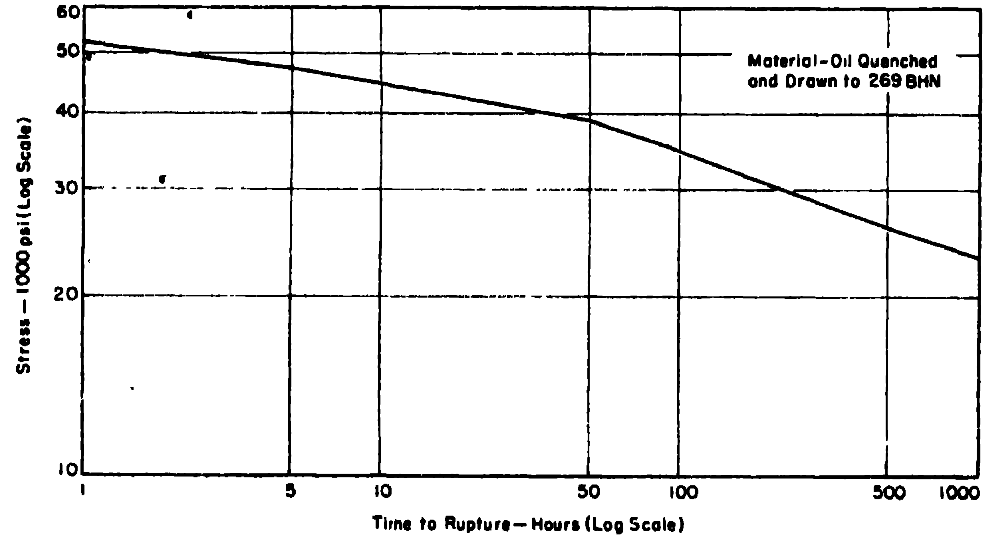


Fig. 23. **Stress-rupture curves for oil quenched and tempered pearlitic malleable iron Grade 80002 at 800° F.**

Using both alloyed and unalloyed pearlitic malleable irons made by air-quenching and tempering to 229 Brinell hardness, Scholz, Doane, and Timmons[81] obtained the values presented in Fig. 24 for exposures at 1100 degrees F. After 100 hours the unalloyed specimens ruptured at 6,000 p.s.i., while after 1,000 hours rupture occurred at about 4,200 p.s.i. The stress-time-to-rupture results of the molybdenum-alloyed pearlitic malleable irons were about 40 per cent better than those of the unalloyed.

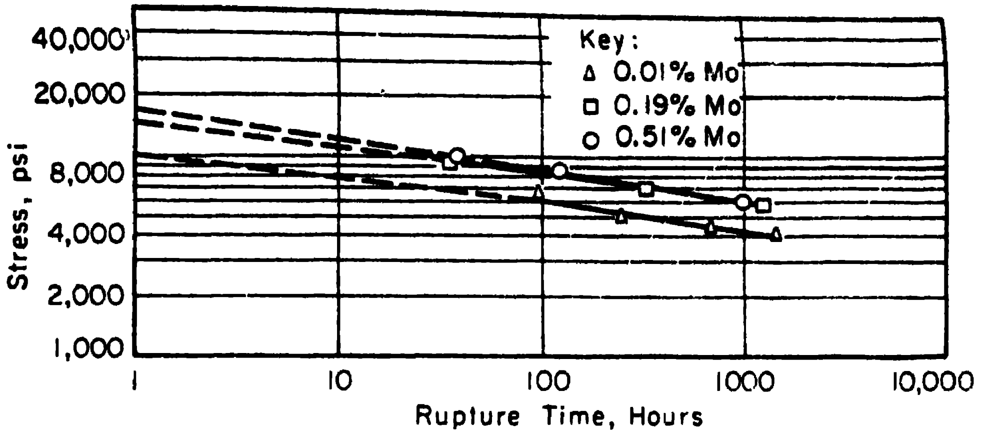


Fig. 24. **Influence of molybdenum alloying on stress-rupture properties of pearlitic malleable iron specimens which were "stabilized" at 1200° F. for 1,000 hours.**

HARDNESS

In short-time exposure tests[80] (15-20 minutes) the hot hardness of three different grades of air-quenched and tempered pearlitic malleable iron dropped slightly between room temperature and 200 degrees F., but was quite constant between 200 and 800 degrees F., above which the hardness decreased substantially. Figure 25 shows this relationship.

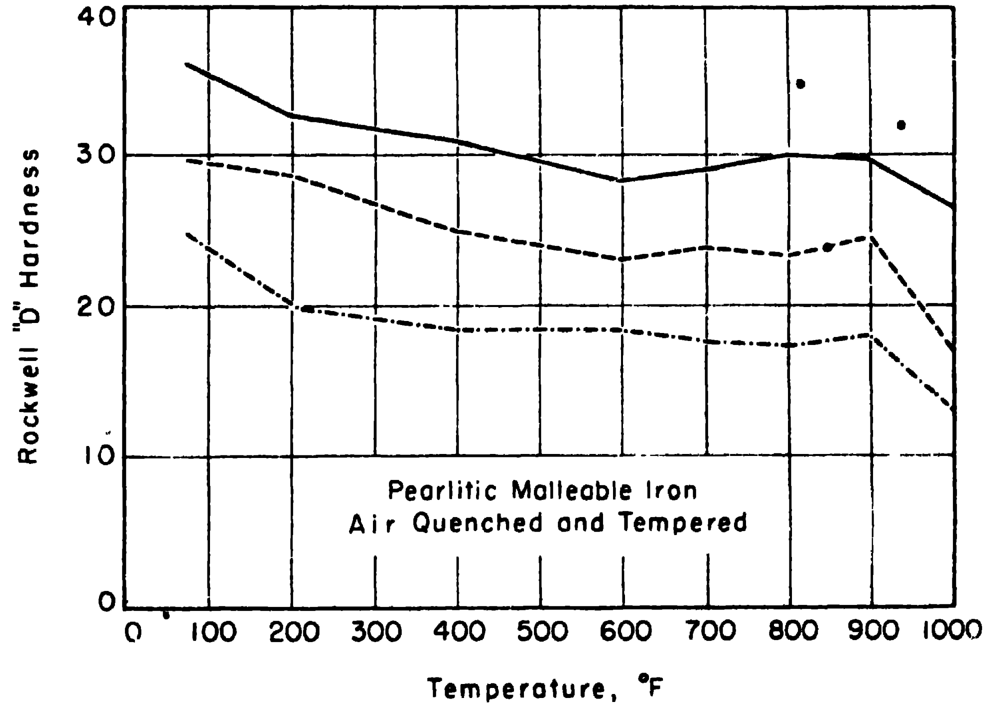


Fig. 25. **Effect on hardness of holding three different air-quenched and tempered pearlitic malleable irons for short times at elevated temperatures.**

Hardness of both unalloyed and molybdenum-alloyed pearlitic malleable iron has also been determined[81] at room temperature after prolonged exposure to temperatures of 1000, 1100, and 1200 degrees F. The results of these tests are plotted in Fig. 26. Lengthy high-temperature exposures of the unalloyed pearlitic malleables caused softening of the metal. The hardness rapidly fell off during the first 25 hours at 1200 degrees F., during the first 100 hours at 1100 degrees F., and during the first 400 hours at 1000 degrees F. Alloying delays the softening reaction and raises the final (minimum) hardness.

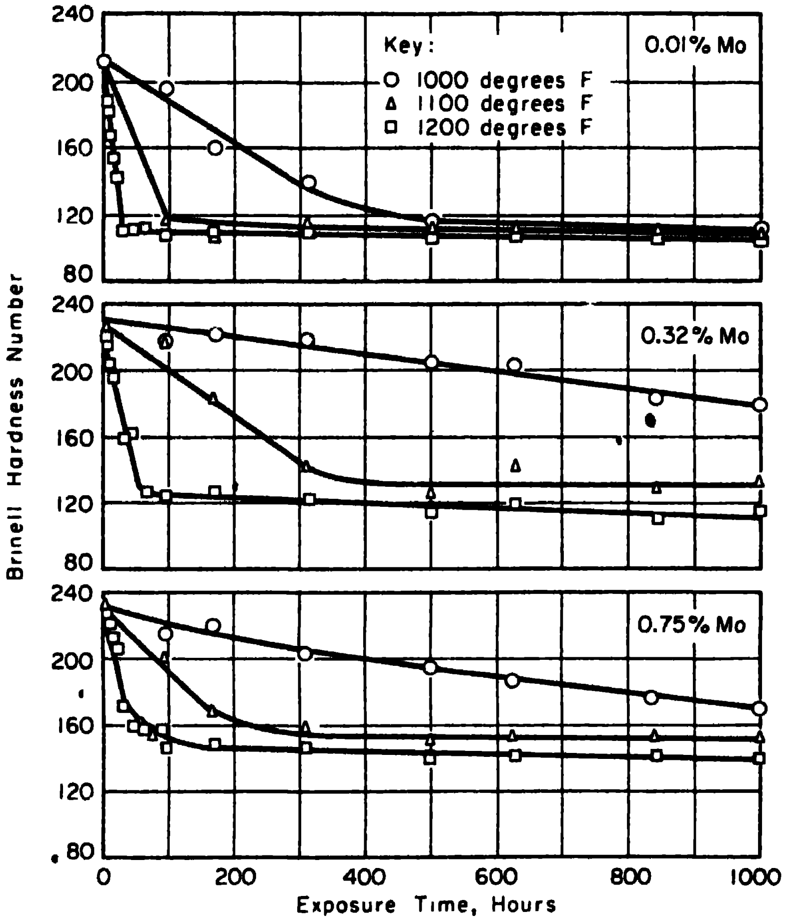


Fig. 26. **Effect of molybdenum on the hardness of pearlitic malleable iron after sustained exposure at elevated temperatures.**

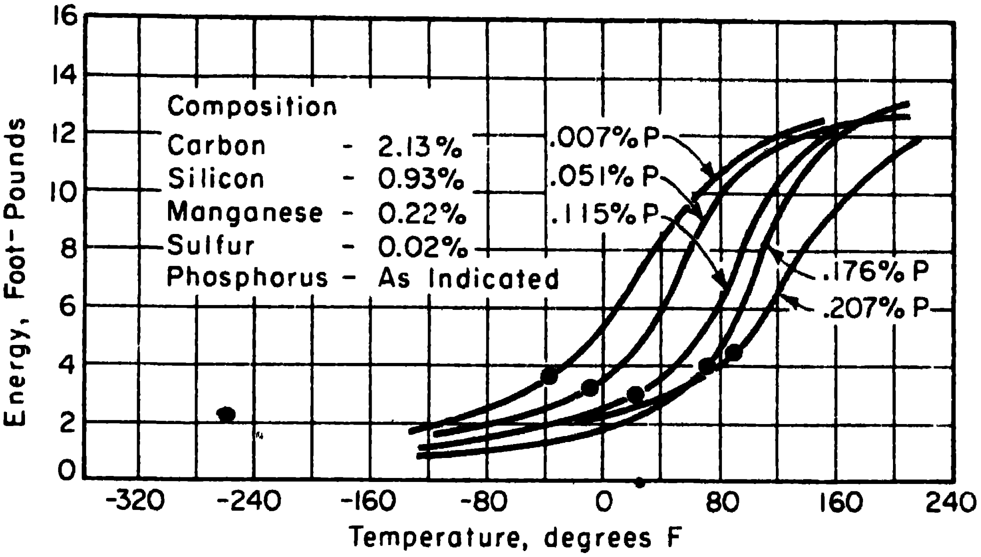
IMPACT PROPERTIES

The room-temperature impact properties of a material may be profoundly altered when the material is chilled or heated. With metals, generally, there is a rather narrow temperature range over which the resistance to impact drops from a high level to a low—or from a tough type of failure to a brittle failure, particularly in the presence of a stress-raiser. This is depicted by the curves of Fig. 27,[40] which also show that the phosphorus content of pearlitic malleable iron exerts an influence on the temperature at which the impact failure is of the brittle type. Figure 28[62] further illustrates the transition temperature range for four different types of pearlitic malleable iron. Similar curves have been constructed by Rosenthal[80] for three different grades of pearlitic malleable.

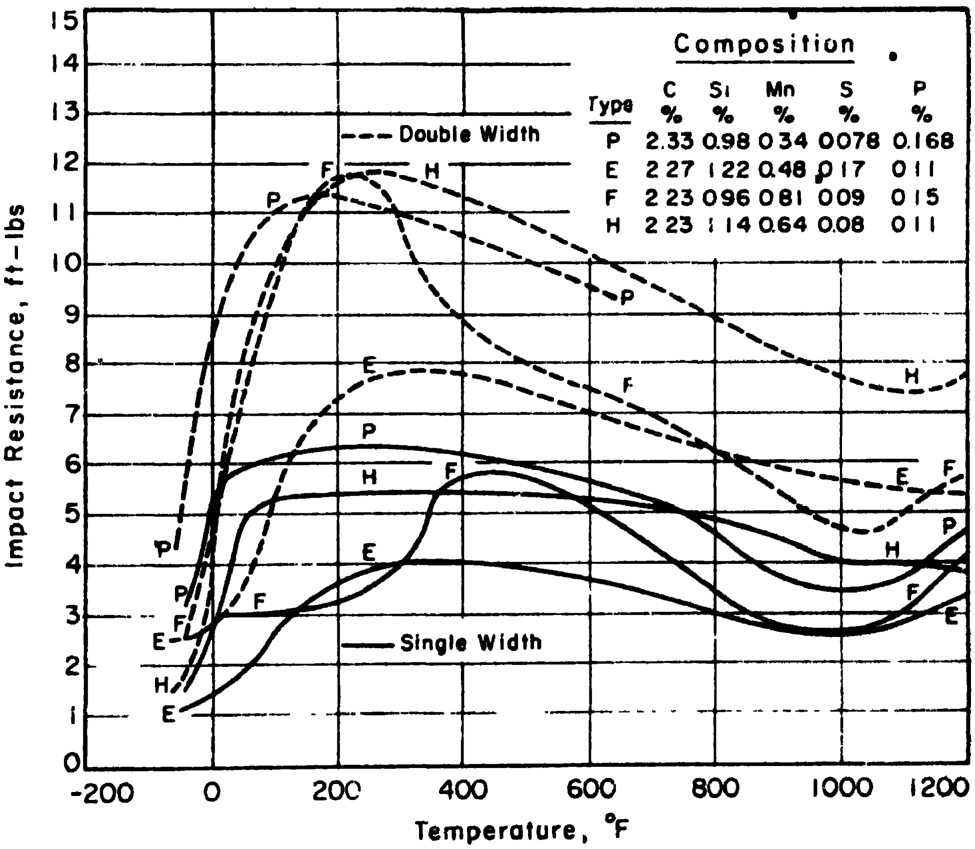
Impact tests at sub-normal temperatures, conducted for this handbook[55] on unalloyed, duplexed pearlitic malleable iron conforming to

A.S.T.M. Grade 45007, gave the following average breaking load results:

Room Temperature	68	foot pounds
10 degrees F.	63.5	" "
-40 degrees F.	56	" "
-60 degrees F.	57	" "



ig. 27. Charpy V-notch transition curves for pearlitic malleable iron of the compo ition shown. Points on the curve indicate nil ductility transition temperatures established by the drop-weight test as a function of phosphorus content.



Composition

Type	C %	Si %	Mn %	S %	P %
P	2.33	0.98	0.34	0.078	0.168
E	2.27	1.22	0.48	0.17	0.11
F	2.23	0.96	0.81	0.09	0.15
H	2.23	1.14	0.64	0.08	0.11

Fig. 28. Charpy V-notch impact tests for four different pearlitic malleable irons over a temperature range from -50° F. to 1200° F.

Investigators at the U.S. Naval Research Laboratory[46] have employed a drop weight test[83] discussed in Chapter V, page 99, to establish the nil ductility point and thus to evaluate the shock toughness of several metals. They found good correlation between this test and the Charpy V-notch impact test curves. For pearlitic malleable irons made by reheating, air-quenching, and tempering to a Brinell range of 160-190, the transition from a tough to a brittle failure occurs within the temperature range of −10 to −70 degrees. Higher silicon and phosphorus contents, and greater combined carbon in the matrix (that is, higher strength, higher-hardness pearlitic malleables) tend to raise the transition temperature.

Tensile impact tests[62] of several different pearlitic malleable irons at temperatures ranging from −40 to 1200 degrees F., ran from 30 to 70 foot-pounds, but failed to show a consistent trend, for which reason this test is regarded as not adapted to determining the NDT temperature of the material. Wedge tests of these irons showed similar scatter.

ENGINEERING PROPERTIES

The usefulness of a material for a given application is determined not only by its physical and mechanical properties but also by its engineering properties. For example, of two materials possessing comparable physical and mechanical properties, one might have certain engineering characteristics that would make it a decidedly wise choice over the other material, because of the ease of subsequent processing and resulting economies, or because of improved service life. The determining factor might be the metal's ability to be cast to closer dimension in intricate shapes, its higher machinability, its greater resistance to wear or corrosion, its faster response to simple hardening treatments, or its combination of several of these and other qualities. Such engineering features as these have dictated the extensive use of pearlitic malleable irons in virtually every phase of modern industry. A number of these engineering properties will be considered in this section.

DESIGN VERSATILITY

The molten white irons from which pearlitic malleable castings are made have high fluidity. This property permits complicated shapes to be cast in pearlitic malleable, as Fig. 29 indicates. Furthermore, good surface finish and close dimensional tolerances are possible. Through coring cavities in the pearlitic malleable castings, appreciable dollar savings may frequently be realized in machining time and in reduction of the over-all weight of the part.

FREEDOM FROM CASTING STRESSES

Pearlitic malleable iron castings, like those made of standard malleable iron, are produced by a process in which heat-treatment is integral

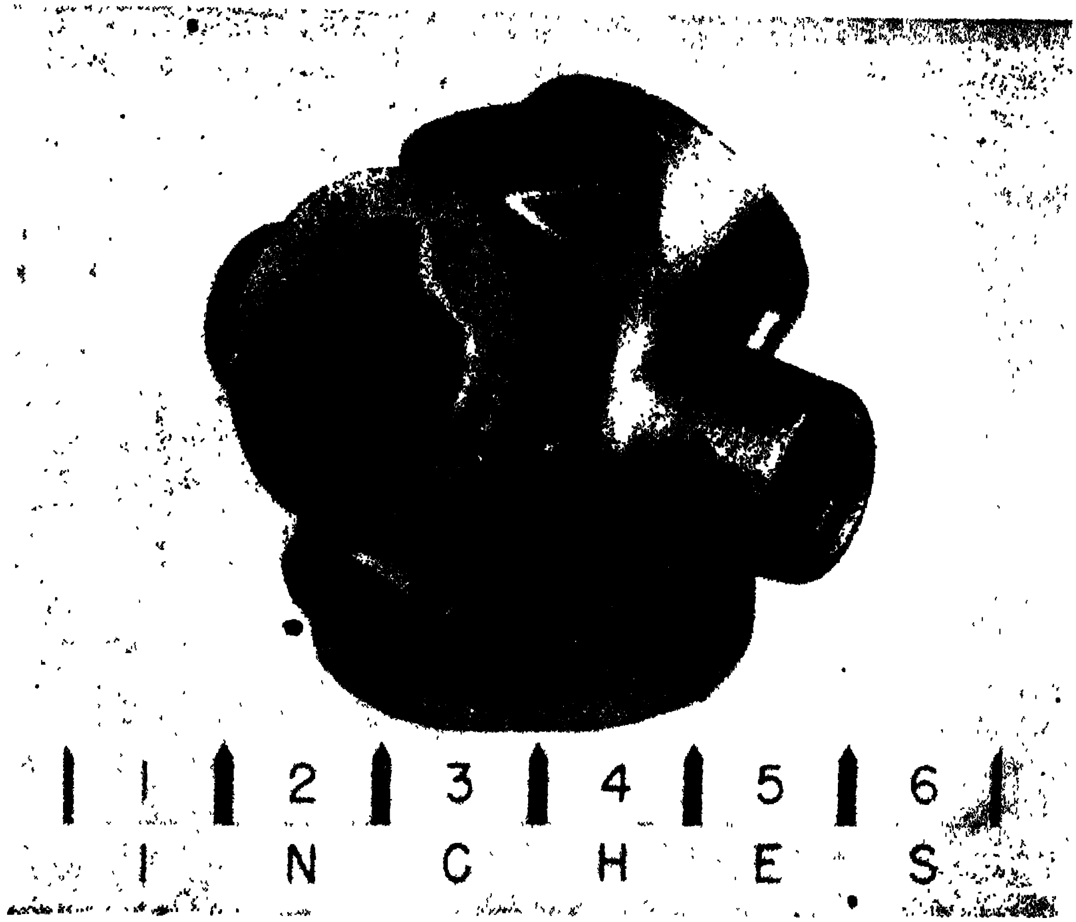


Fig. 29. The complicated three-way pipe threader is readily cast in pearlitic malleable iron due to its high fluidity.

and essential. Any internal stresses, which may have occurred as the casting solidified and cooled, are removed by this heat-treatment.

MACHINABILITY

Pearlitic malleable irons machine readily, but, because of their combined carbon content, somewhat less readily than the standard malleables. Since a wide range of hardness and structure is provided in pearlitic malleable irons, the degree of machinability suitable for a particular requirement is readily available. The Brinell hardness is a reasonably reliable measure of the comparative machinability of pearlitic malleable irons of the same grade, chemical analysis, and heat-treatment. General experience indicates that, in machining pearlitic malleable irons, the higher the hardness, the better the final finish, for a given structure.

The machining of malleable iron is discussed in detail in Chapter X. In general, the best results are obtained through using greater feeds and lower speeds for pearlitic than for standard malleable iron, i.e. taking a fairly heavy cut.(16) The experience of one of the larger motor companies has been that when this plan is followed, the pearlitic malleable irons are 20 to 40 per cent more machinable than steel bar stock or drop forgings of the same Brinell hardness number, and that tool life per grind is 20 to 100 per cent longer.[84]

This practice is illustrated in the manufacture of a two-piece differential case of pearlitic malleable iron with tensile strength of 80,000 p.s.i. The case is machined on a turret lathe with J-Stellite tools. A roughing cut of one-eighth to $\frac{3}{16}$-inch is made at 100 surface feet per minute with a feed of 0.040-inch per revolution. Finishing cuts are made at 129 to 165 surface feet per minute.[85] Another type of pearlitic malleable iron with a Brinell hardness number of 170 to 180 is regularly machined dry at higher cutting speeds than can be used for A.I.S.I. 1020-1030.[66]

That excellent surface finish is attainable with machined pearlitic malleable iron is illustrated in Fig. 30.

In the production of shot gun frames such as that shown in Fig. 31, machining was a major factor, since the frames were originally hogged out of steel forgings. Conversion to pearlitic malleable castings eliminated much costly machining not only through coring of the voids but also because of the superior machining qualities of the cast material. The savings in machining alone exceeded the cost of the casting. Moreover, an excellent machine finish was obtained.[86]

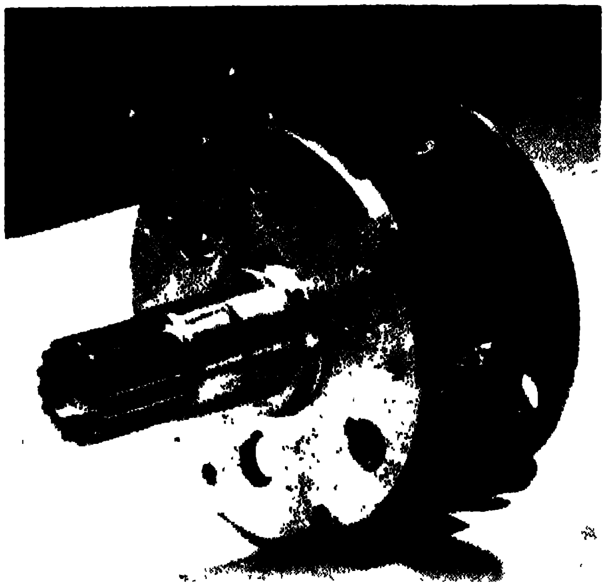


Fig. 30. **The excellent surface finish attainable with machined pearlitic is illustrated by this automotive power take-off planet carrier.**

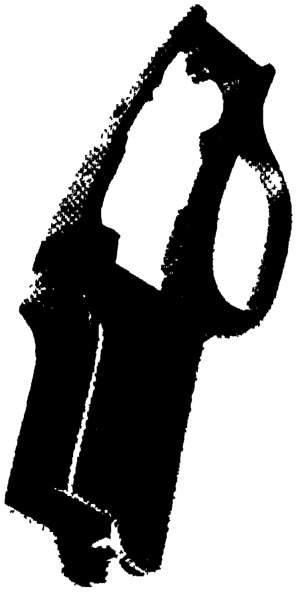


Fig. 31. **A fine surface finish and a substantial cost reduction resulted when this shotgun frame was converted to pearlitic malleable iron.**

When machinability of pearlitic malleable iron was evaluated by drilling tests and was expressed as the horsepower required to remove a cubic inch of material per minute it was found that machinability appears to bear some relation to yield strength and hardness, as is shown by Figs. 32 and 33.[87]

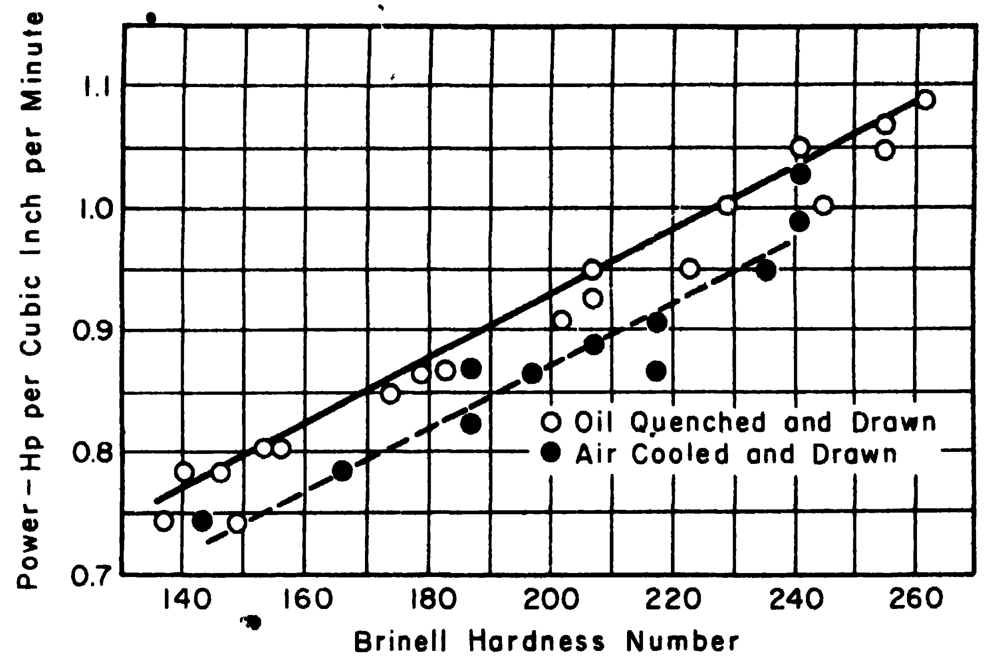


Fig. 32. **Horsepower required to remove a cubic inch of material per minute drilling as a function of the hardness of pearlitic malleable iron.**

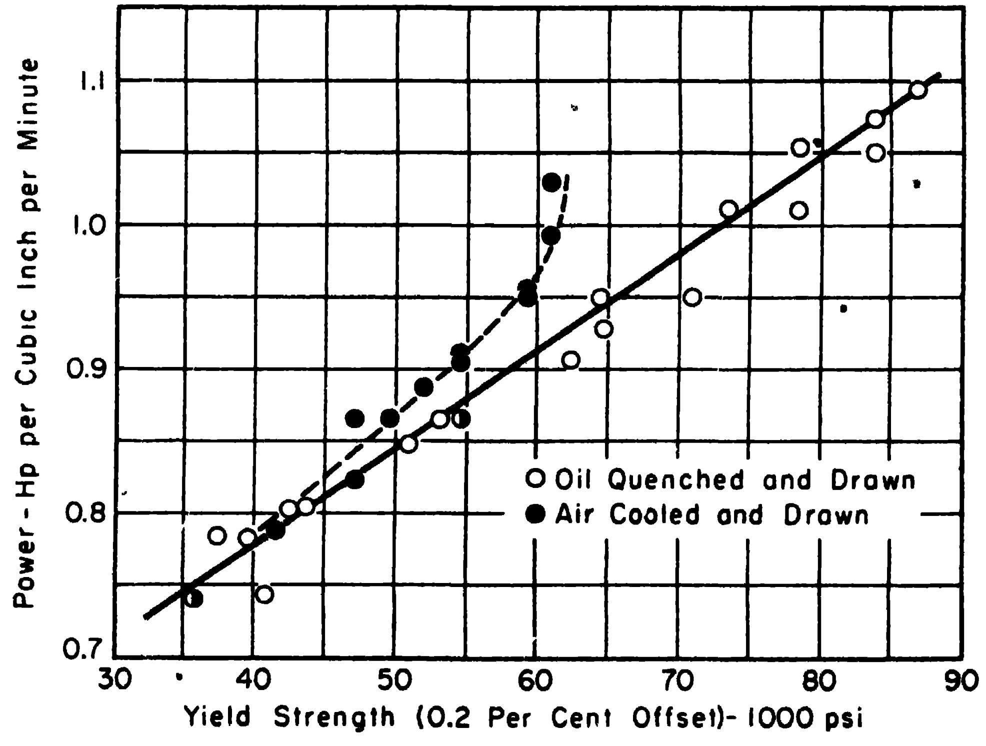


Fig. 33. **Horsepower required to remove, by drilling, a cubic inch of material per minute as a function of the yield strength of pearlitic malleable iron.**

A series of tests to determine the average watt-hours per cubic inch of metal removed showed that a pearlitic malleable iron of 211 Brinell had 73 per cent of the machinability of a standard malleable iron with a Brinell hardness number of 137. The addition of 1 per cent copper increased the machinability of the pearlitic malleable iron to 85 per cent of that of the standard malleable iron.[66]

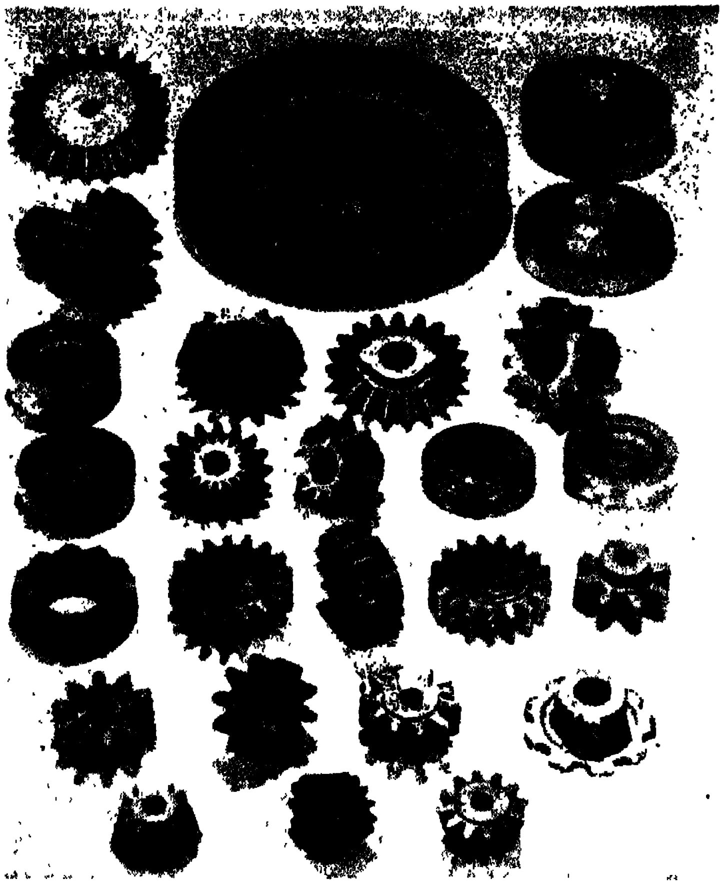


***Fig. 34.* A sampling of the many kinds of pearlitic malleable gears and blanks.**

WEAR RESISTANCE

Pearlitic malleable irons are generally preferred for applications in which wear resistance is a desirable property. Though not all pearlitic malleable irons have equal resistance to wear, the higher indentation hardness and stronger structure available through proper composition and heat-treatment produce excellent performance in such parts as gears, camshafts, chain links, and rolls. For gears such as those shown in Fig. 34 hardened pearlitic malleable iron is often specified.

Service wear tests[78] have been made on a passenger-car crankshaft involving 13 different engines driven 50,000 or 100,000 miles each. Shafts of pearlitic malleable iron and forged A.I.S.I 1046 steel were compared. Wear test measurements made after the shafts had been subjected to severe service conditions indicated that wear was about equal for both materials.

Several of the pearlitic malleables are particularly well adapted for use as bearings, where their excellent non-galling properties have made possible the elimination of the bronze bushing formerly used.[88]

HARDENING PEARLITIC MALLEABLE IRONS

The most useful microconstituent for imparting hardness to ferrous alloys is carbon in the combined form (Fe_3C.). The quantity, form, and distribution of this combined carbon will determine the over-all hardness of the metal. In sharp contrast to standard, or ferritic, malleable iron, whose matrix is free from combined carbon, pearlitic malleable irons contain some 0.3 to 0.9 per cent carbon in the combined form. Since this constituent can be readily transformed by a simple heating and quenching treatment into the hardest form of combined carbon, pearlitic malleable castings can be selectively hardened with ease.

The depth of hardening is controlled by the rate of heat input. The degree of hardening is regulated by the time and temperature of the hardening treatment, by the rate of quenching, and by any subsequent tempering treatment. If there is not enough combined carbon in the matrix of the castings to provide the maximum hardness desired, additional combined carbon may be obtained from within the casting itself through re-solution of carbon from the existing graphite nodules. This is accomplished by modifying the time-temperature hardening cycle sufficiently for this relatively slower reaction to take place. The quench that follows retains the dissolved carbon in the combined form.

Since the hardening treatment of pearlitic malleable irons involves only heating and quenching, any of the several common heating methods may be employed—induction, flame, salt or lead bath, or conventional heat-treating furnaces. Where a shallow depth of hardening is desired, the induction and flame methods are preferable. If the depth of hardening is unimportant, any of the procedures can be utilized. If decarburization at the casting surface should present a problem, as in muffle furnace heating, recourse to neutral or reducing atmospheres may prove helpful.

The quench rate is controlled by the quenching medium, which in turn determines the maximum obtainable hardness. Various media may be employed, including water, brine, oil, salt, or lead baths, aqueous solutions of special proprietary compounds, or air. While water or brine will provide the fastest cooling rate, it may prove too drastic for many applications, particularly if the castings are intricate or if high hardening temperatures are employed, resulting in quench cracks. If these should occur, the hardening temperature should be lowered, a less extreme quench medium should be tried, or both.

If desirable, the hardened structure may be tempered at any temperature up to about 1300 degrees F., the higher temperatures resulting in greater softening.

It is impossible to prescribe a universal hardening procedure for all pearlitic malleable irons. The response to hardening will depend upon such factors as section thickness to be hardened, distribution of the temper carbon, chemical composition of the iron, type and quantity of the combined carbon already in the matrix, and the kind of heating equipment available for the hardening treatment. For pearlitic malleable castings that are to be subsequently selectively hardened, it is recommended that there be sufficient combined carbon in the matrix to give a Brinell hardness number of 197 or higher.

General conclusions of marked interest concerning the surface hardening of pearlitic malleable irons resulted from studies conducted at the University of Michigan under the sponsorship of the Malleable Research Committee of the American Foundrymen's Society.[89] For induction hardening, the investigators reported, proper time and power input were controlling factors which, when properly selected, gave satisfactory results with all the irons tested. Chemical composition, within the limits investigated, showed no noticeable effect on the response of the irons to hardening. A dense pattern of finely spheroidized cementite consistently yielded the highest hardness at 0.060-inch and maximum depth of case at Rockwell C hardness of 50 over the range of power and time investigated. A microstructure consisting of a matrix of ferrite and coarsely spheroidized cementite was the least satisfactory. For flame hardening, it was found that temperature control is critical, that an increase in manganese in the chemical composition is accompanied by an increase in hardness and depth of case in irons of similar lamellar microstructure, that an increase in heating time produces a more uniform and deeper hardened case, and

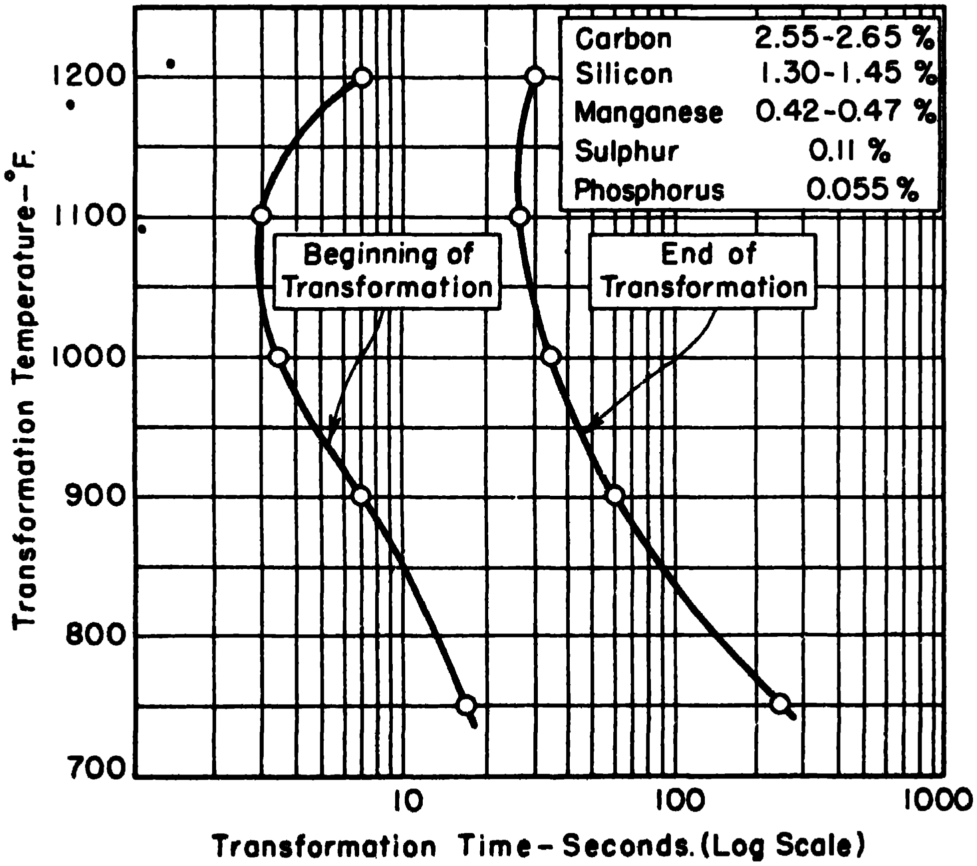


Fig. 35. **Semi-logarithmic plot showing approximate beginning and end of isothermal transformation at various subcritical temperatures. Material used was a spheroidized pearlitic malleable iron which has been austenitized at 1600° F. for 30 minutes.**

that to secure Rockwell C 50 at 0.060-inch, a water quench is necessary. A dense pattern of finely spheroidized cementite gave consistently the best results, whereas a microstructure made up chiefly or entirely of coarse spheroids gave the poorest. Bulls-eye structure, it was found, did not appreciably affect uniformity of the hardness of the case. whether flame or induction hardening was used. With either method, an increase in heating time under the same conditions gave higher case hardness, a deeper case, and a more homogeneous microstructure.

Localized or through hardening has been accomplished satisfactorily by immersion of pearlitic malleables in a lead or salt bath to the depth necessary, at temperatures of 1450 to 1700 degrees F. The temperature will depend upon the type of pearlitic malleable iron, the subsequent quench rate, and the intricacy of the casting. Hardness of Rockwell 50 C minimum was attained by immersion of sections of one-inch or less of 163-207 Brinell hardness range for approximately five minutes, followed by an oil quench.[90] When the pearlitic malleable to be treated is in the 197-241 Brinell hardness range, immersion for 2.5 or 3 minutes is adequate for sections up to an inch.[90] Although the material of lower original hardness requires about two additional minutes for the hardening operation, it possesses the advantage that the original machining operation on it may be more economically performed.

A portion of a typical time-temperature-transformation curve, developed for one particular unalloyed pearlitic malleable iron, is shown in Fig. 35.[91] As an indication of the hardenability of pearlitic malleable, Fig. 36[78] shows the results obtained on standard, end-quenched specimens as compared to those of a forged A.I.S.I. 1046 steel. In another study[92]

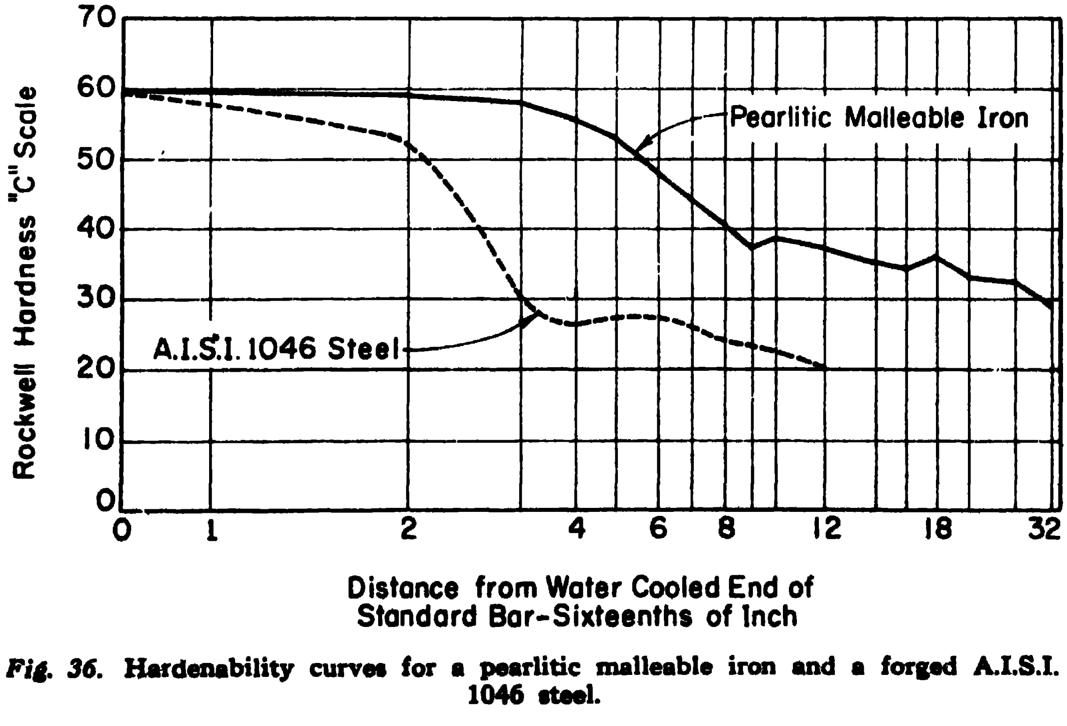


Fig. 36. **Hardenability curves for a pearlitic malleable iron and a forged A.I.S.I. 1046 steel.**

Jominy tests were performed on test bars cast 1¼-inch in diameter by 6 to 8 inches in length, heat-treated by conventional methods for producing pearlitic malleable iron, some liquid-quenched, some air-quenched. It was found that hardenability curves were similar regardless of the quenching method and that pearlitic malleable iron has end-quench hardenability similar to that of A.I.S.I. 1340, 4045, and other alloy steels.

The nitriding process has been reported[93] to be successful in imparting a shallow hardened case in such parts as shifter forks and small gears. Treatment for three hours at 1390 degrees F. in an atmosphere of carburizing gas and ammonia gave a case depth of 0.004-inch.

Some typical examples of the economic advantages of conversions, made possible by the use of localized and surface hardened pearlitic malleable castings, are as follows:

Conveyor trolley wheel—The manufacturer replaced a forged A.I.S.I. 1040 steel trolley wheel with pearlitic malleable iron in the 197-241 Brinell range and induction-hardened the rim to Rockwell 50 C minimum to a depth of $\frac{1}{16}$-inch with a liquid quench.[94]

Automotive rocker arms—Originally, most rocker arms were A.I.S.I. 1020 steel, carburized and hardened. Some were A.I.S.I. 1035 steel, hardened on the pad end. Pearlitic malleable iron rocker arms were hardened on the pad end by immersion in a salt bath at around 1600 degrees F. or induction-heated followed by an oil quench. A representative group of rocker arms is shown in Fig. 37.

Truck crankshaft sprocket—Formerly machined from steel bar stock,

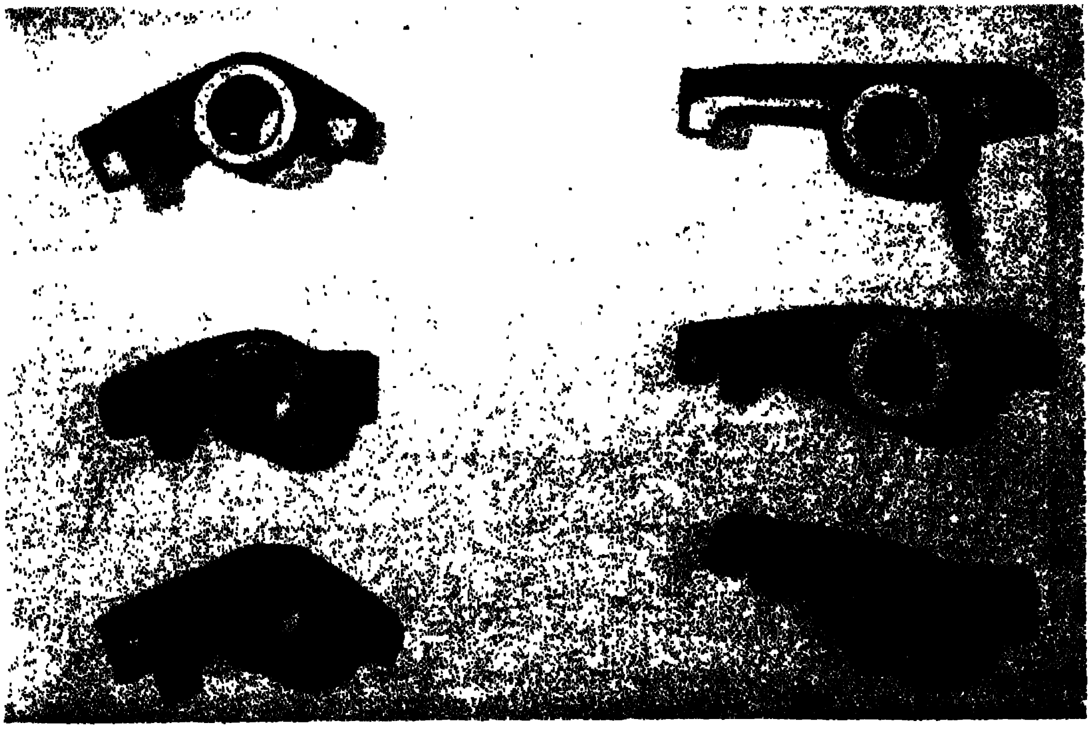


Fig. 37. **This picture shows various designs of pearlitic malleable automotive rocker arms.**

this sprocket is now produced in pearlitic malleable iron. Following machining, the teeth are flame-heated for about 6.6 seconds to a temperature sufficient to produce a minimum Rockwell 55 C hardness after an automatic quench in oil held at a temperature of 90 degrees F.

CORROSION RESISTANCE

In numerous industries where corrosion of pump parts, chain links, elevator buckets, valve bodies, and rolls is involved, pearlitic malleable irons are widely specified. The inclusion of copper increases resistance to corrosion.[93] Fig. 38 shows an application which takes full advantage of the corrosion resistance of pearlitic malleable.

The average service life of these pearlitic malleable chain links, circulating through highly corrosive sewage, is 15 years despite intermittent wetting and drying periods.

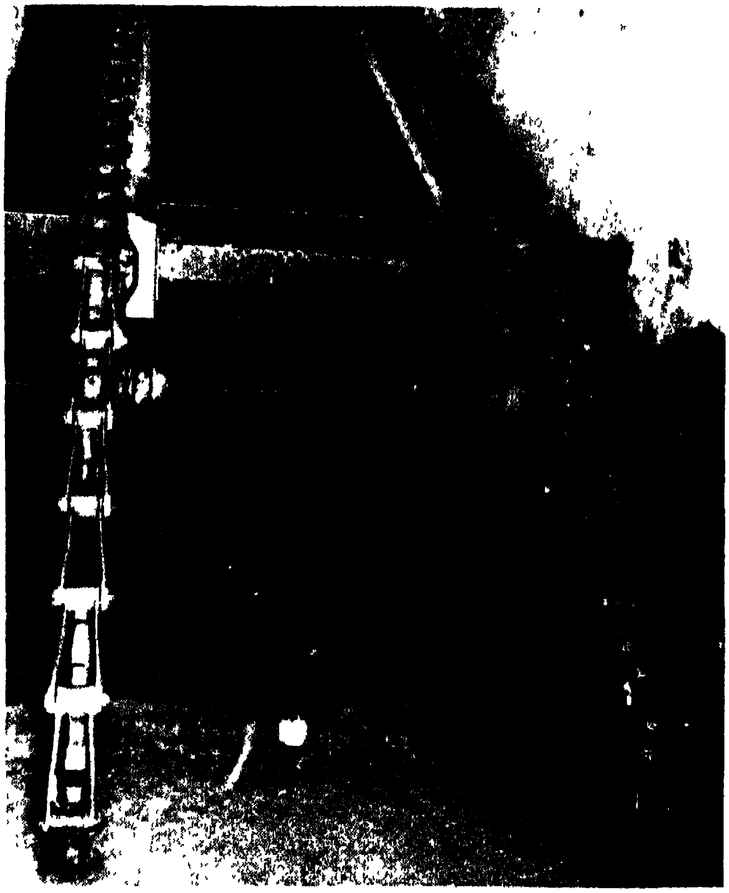


Fig. 38. **Pearlitic malleable iron chains used in highly corrosive sewage processing plants. Service life of the chains runs as long as 22 years, with an average life of 15 years.**

In Fig. 39, the oxidation penetration of pearlitic malleable iron is compared with some other common ferrous alloys after long time exposure in air at 1300° F. The rate of oxidation penetration of pearlitic malleable and the metals listed for Fig. 39 is illustrated in Fig. 40. Galvanizing and other protective coatings, such as those discussed in Chapter V, can be utilized to provide added corrosion resistance as they are with standard malleables.

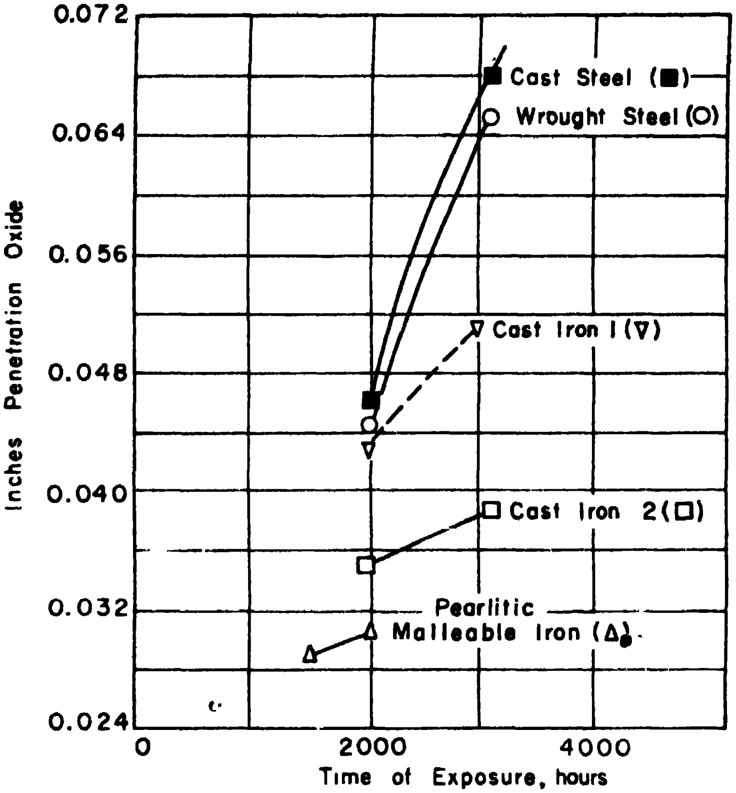


Fig. 39. Oxidation penetration of pearlitic malleable iron compared with some other ferrous alloys after exposure for long periods in air at 1300° F. The cast and wrought steels were of the 1030 type; cast iron No. 1 had a higher carbon equivalent of 3.83% than cast iron No. 2 (C.E. = 3.17%).

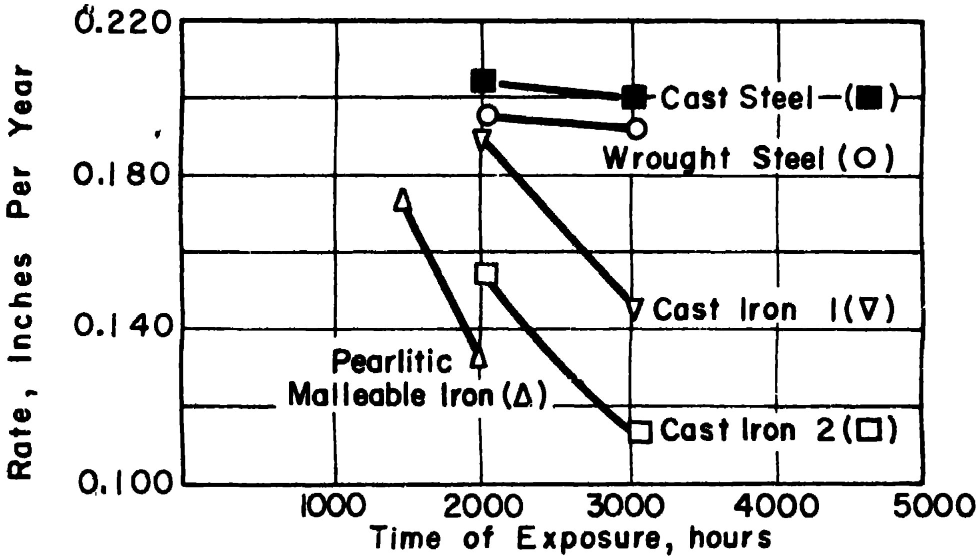


Fig. 40. Oxidation rate for pearlitic malleable iron and some other ferrous materials when exposed for long times in air at 1300° F.

WELDING

The great readiness with which pearlitic malleable iron is hardened, because of the combined carbon already present in its structure, makes it generally unsuitable for welding. The problems of welding standard malleable iron, discussed in Chapter V, are accentuated in efforts to weld pearlitic malleable iron. The formation of a brittle, low-strength white iron layer under the weld bead, caused by the melting and rapid freezing of the malleable iron, is one undesirable result. The pearlitic structure adjacent to the white iron in the welding zone also is altered through the re-dissolving of some temper carbon.

Pearlitic malleable iron, in cases where applicable, may be brazed through the use of techniques similar to those discussed for standard malleable iron in Chapter V.

MACHINING ALLOWANCE

The size and shape of the castings determine the machining allowance that should be made. Small and simple parts can be made with as little as $\frac{3}{64}$-inch stock, particularly if the entire piece is cast in one half of the mold. For large castings as much as $\frac{1}{8}$-inch may be required. In general, however, an allowance of $\frac{1}{16}$- to $\frac{3}{32}$-inch per surface has been found satisfactory on the majority of pearlitic malleable castings.

A detailed discussion of recommended machining practices for pearlitic malleable iron will be found in the chapter dealing with machining.

COINING ALLOWANCE

Pearlitic malleable parts can be coined to very close dimensions. Grades heat treated to lower hardness levels coin more readily than those having high hardness.

Coining is widely used to reduce or eliminate machining operations on pearlitic malleable castings. The degree to which pearlitic malleable castings can be coined depends on several factors, namely, the grade, the area and shape of the surface to be coined, the capacity of the coining equipment, and whether the operations are performed on a hot or cold product.

For example, the hubs of automotive rocker arms of grade 53004 pearlitic malleable are cold-coined face to face to a tolerance of plus or minus .010″. The area of the coined surfaces which approximate .75 square inches are subjected to a pressure of about 100 tons.

Pearlitic malleable castings are also hot-coined under controlled temperature in single or multiple coining operations to closer tolerances than is attainable by cold coining.

VII

ALLOYED MALLEABLE IRONS

ALLOYED malleable irons are those whose properties result, in part, from the addition of alloying elements not normally present in significant quantities in standard, or ferritic, malleable iron. The two principal kinds are: (1) copper-alloyed malleable iron, and (2) copper-molybdenum-alloyed malleable iron. Both are commercially produced to meet particular requirements. Copper is used as an alloy in malleable iron to increase resistance to corrosion and to increase tensile strength and yield point at very slight reduction in elongation. Copper and molybdenum are added in combination as alloys to produce a malleable iron of superior corrosion resistance and mechanical properties.

These alloyed malleable irons differ from the pearlitic malleable irons in that they are completely malleablized, deriving their particular characteristics from the effect of the special chemical composition on the ferritic matrix of the castings. The kind and quantity of alloys will be determined by the service requirements of the castings. Aside from this addition of special elements to the molten iron, the processing of alloyed malleable irons is identical with that of standard malleable. They are cast as white iron, and their structure is subsequently transformed by a malleablizing anneal into ferrite and temper carbon.

COPPER-ALLOYED MALLEABLE IRON

Copper may be added primarily to improve the corrosion resistance of malleable iron, to increase its strength, or both. Besides these attributes, however, copper will raise the hardness of the iron, shorten the duration of the malleablizing anneal, reduce the susceptibility to temper embrittlement, enhance fatigue or endurance strength, and render the metal amenable to precipitation heat-treatments.

Small amounts of copper, dissolved in iron, strengthen the ferrite.

When the copper content exceeds its solubility limit in ferrite at room temperature (approximately 0.5 per cent), the strength properties of malleable iron continue to increase with increase in copper content up to about 1.75 per cent, above which tensile strength levels off at about 60,000 pounds per square inch and yield strength at about 45,000 p.s.i.[96] The yield ratio (ratio of yield to tensile strength), which for unalloyed standard malleable iron is commonly between 0.6 and 0.7, is increased to approximately 0.75 by copper additions over about 1 per cent. To some extent, the effect of copper is a function of the chemical composition of the metal, decreasing with decreasing carbon content. Such standard malleables as may normally have tensile strength in excess of 55,000 p.s.i. without copper additions are not substantially affected by the addition.

In addition to raising the tensile and yield strengths of malleable iron, copper additions improve the fatigue strength in about the same proportions as the tensile strength, viz., 3,000 to 5,000 p.s.i. for 1 to 1.25 per cent added copper. Hardness likewise is increased, as is illustrated by Fig. 1.

The graphitizing tendency during both solidification and malleableization is increased by copper in malleable iron. Since copper has about one-tenth as great an effect on primary graphitization as silicon, it is

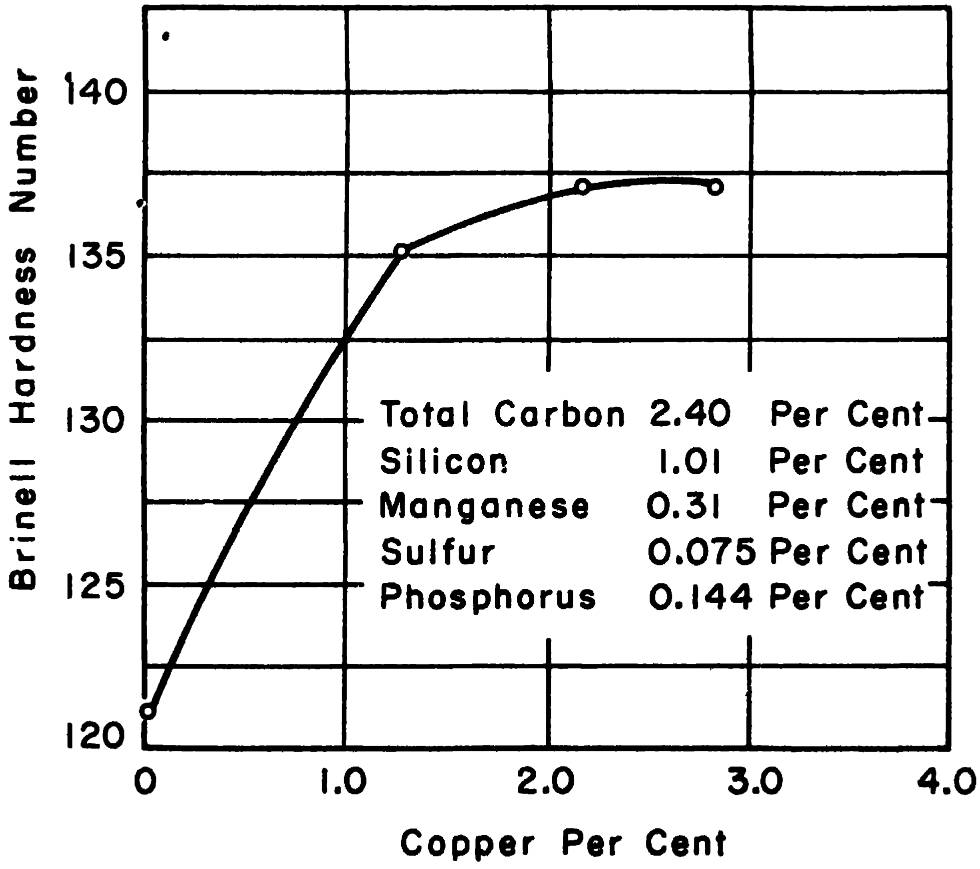


Fig. 1. **Relationship between copper content and hardness for a malleable iron of the composition shown.**

preferable to have 0.1 per cent less silicon in the iron when making a 1 per cent copper alloyed malleable so as to prevent the formation of primary graphite.[97] During heat-treatment copper refines the temper carbon, especially if the castings are preheated or are heated slowly to the first-stage graphitizing temperature. This hastens completion of malleablization, thus shortening the annealing cycle.[98,99]

Resistance to corrosion in normal and industrial atmospheres is improved by alloying malleable iron with copper, even with additions of only 0.25 per cent.[12] Copper contents of about 1 per cent raise the resistance of malleable iron to smoke corrosion by about 25 per cent.[100] Copper-alloyed malleable iron is commonly specified for castings that are to be constantly exposed to weather, such as those on bridges, railroad freight cars, tracks, and switch stands, where good resistance to corrosion is necessary. For the same reason it is specified for pipe fittings, chain links, and conveyor buckets.[96]

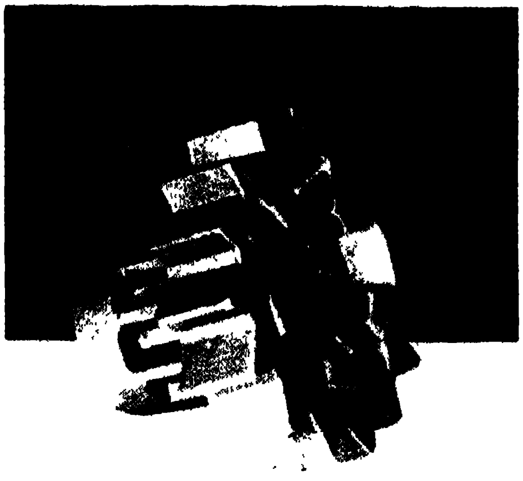


Fig. 2. A copper-molybdenum alloyed malleable iron pinion gear used for freight-car handbrakes.

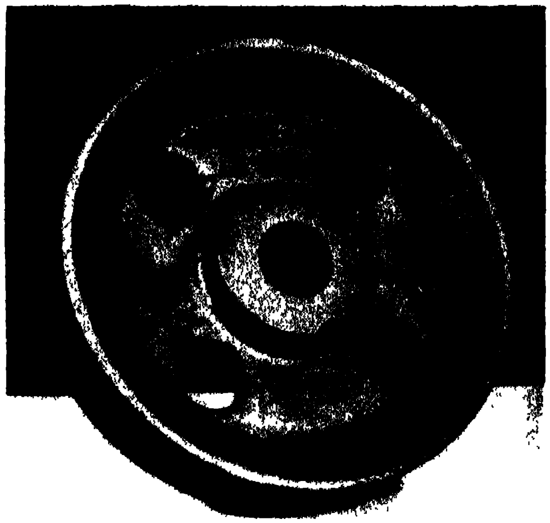


Fig. 3. Alloying with .30% molybdenum and .75% copper increases the wear resistance of the sheave for a hydraulic crane.

The strength properties of malleable iron containing 1 per cent or more copper can be further increased by a precipitation hardening treatment. When copper-alloyed malleable iron is reheated to 1350 to 1375 degrees F. for one hour, then air cooled and aged at 930 degrees for three to five hours, the copper is precipitated as submicroscopic particles. Such treatment increases the tensile strength about 5,000 to 10,000 p.s.i., yield strength about 10,000 p.s.i., and hardness about 30 Brinell hardness numbers. Elongation is slightly decreased.[96] Malleable irons which normally have strength in the higher ranges are less affected by this treatment.

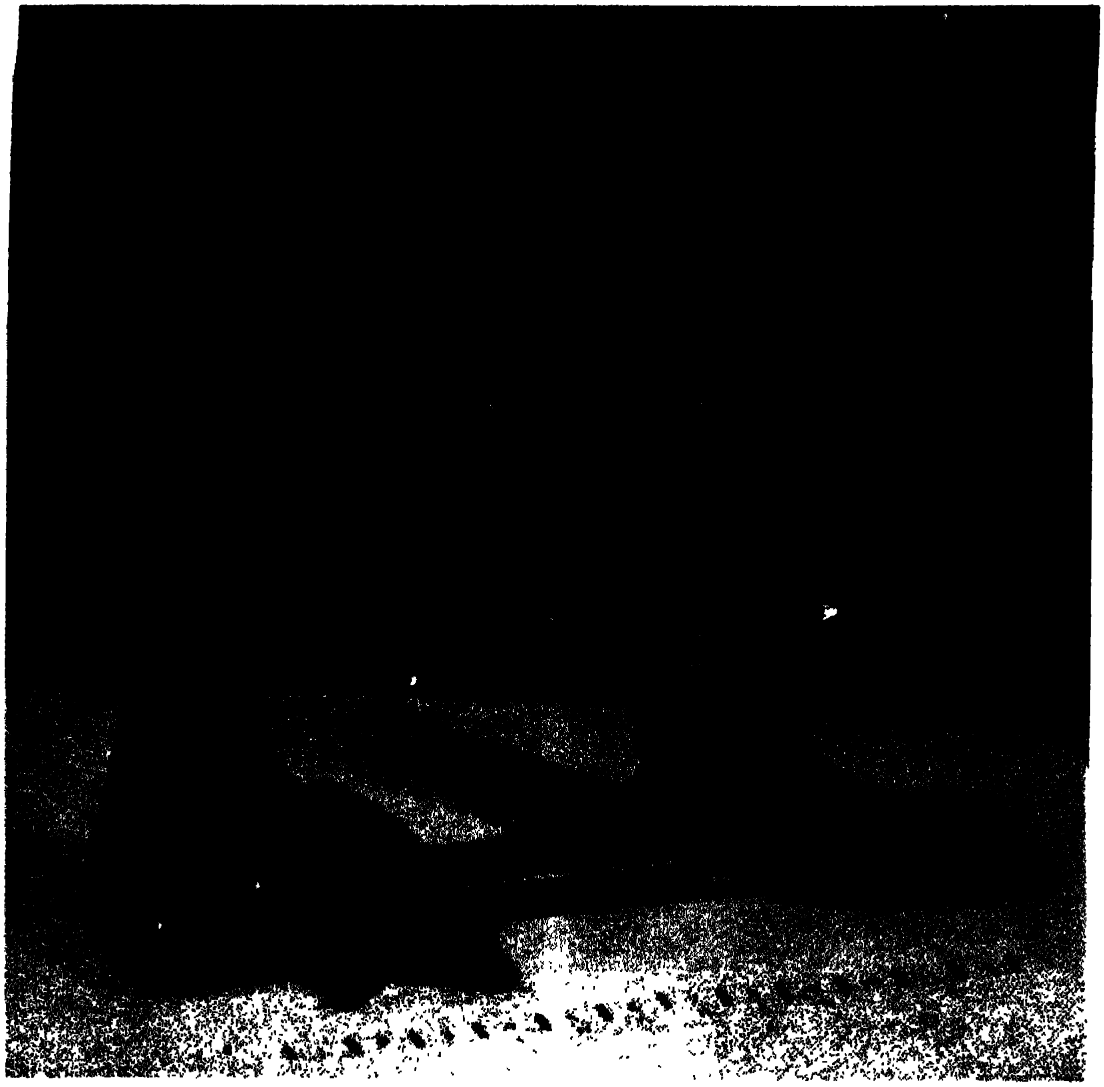


Fig. 4. **This copper-molybdenum alloyed malleable iron casting is used for holding large reels of cable in freight-cars during shipping.**

COPPER-MOLYBDENUM-ALLOYED MALLEABLE IRON

Molybdenum additions up to 0.5 per cent increase the tensile strength of malleable irons by as much as 7,000 p.s.i. and the yield strength as much as 3,000 p.s.i.[101] Because of the carbide-stabilizing influence of the molybdenum, however, the normal malleablizing cycle must be lengthened in order to secure full graphitization of the metal.

It is more common practice in the manufacture of molybdenum-bearing alloyed malleable iron to add also enough copper to offset the carbide-stabilizing effect of the molybdenum, thereby making it possible to produce a fully ferritic matrix without extending the normal malleablizing cycle. To balance some 0.2 to 0.4 per cent molybdenum, it is customary to add 0.5 to 1.25 per cent copper. This not only promotes graphitization but also contributes to the strength, hardness, and corrosion resistance of the castings. In some instances nickel, rather than molybdenum, is used in conjunction with copper, this alloy combination malleablizing readily.

The mechanical properties of copper-molybdenum-alloyed malleable iron are as follows:[101]

Tensile strength, p.s.i.	58,000 – 65,000
Yield point, p.s.i.	40,000 – 45,000
Elongation, per cent in 2 inches	15 – 20
Brinell hardness number	135 – 155

The machinability of this high-strength, alloyed malleable iron is approximately the same as that of Grade 35018 standard malleable.

The material may be further strengthened by a special heat-treatment following malleablizing. This consists of quenching from 1300-1350 degrees F., and aging for 3 to 5 hours at about 900 degrees F.

Alloyed malleable iron containing 0.75 per cent copper and 0.4 per cent molybdenum has replaced steel in certain bearing retainers and other applications.[96] It has also found wide usage in pipe wrench handles, freight car hand-brake pinions and ratchet wheels, mold clamps for foundries, and pulley wheels for hydraulic cranes.[102]

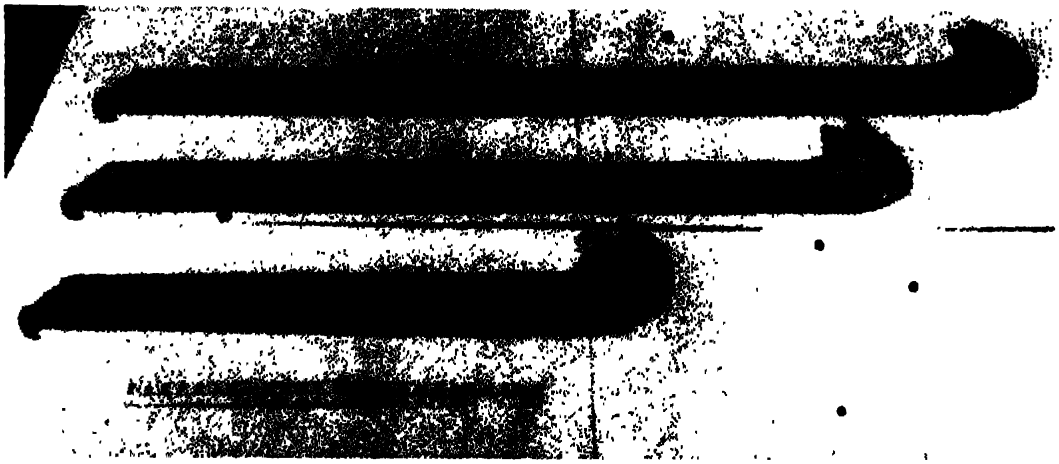


Fig. 5. The copper-molybdenum alloyed flask clamp has wide usage in the foundry industry.

EFFECT OF ALLOYS

Though copper and molybdenum are the alloys principally in use in the manufacture of alloyed malleable irons which are marketed as such, many others are used to secure special results. Among these are bismuth, boron, chromium, manganese, nickel, sulfur, and tellurium. Alloys are customarily classed as graphitizers, retarders, or both, depending upon their effect on graphitization.

Some alloys affect the graphitizing tendency when the molten metal is cast; others have more effect in the heat-treating operation. Several combinations of alloys utilize this fact by incorporating a retarder to make the iron solidify without primary graphite and a graphitizer to facilitate precipitation of temper carbon. The specific alloying elements, their effect on the iron, and the mechanism of that effect are discussed in detail in Chapter XI, "The Metallurgy of Malleable Iron."

VIII

THE DESIGN OF MALLEABLE IRON CASTINGS

CASTING comes closer than any other production process to the manufacture of a desired finished part in one piece and by one operation. To make the most of the casting process, thorough consideration should be given to the design of the proposed casting in advance of production. When this is done in the manufacture of malleable iron, producer and user can reap the full benefit of the fluidity of the basic metal from which malleable iron is produced and the ease with which light and heavy sections may be combined in one part and yet maintain uniform metal structure and properties throughout.

Design factors with which the design engineer and the foundry engineer must reckon can somewhat arbitrarily be divided into two groups: those having to do with the special requirements of the casting process itself, and those having to do with the properties of the metal to be used and with the demands of the future life of the casting. This classification is convenient, but it is not rigid; the two kinds of factors influence each other in many ways, as will appear in subsequent discussions. A quick view of essentials in the casting process hence is next given, as background.

Basically, the purpose of the process of casting is to produce a metal part in a desired shape by solidification of the metal from the molten state in a properly shaped mold cavity. In usual foundry practice, molds are formed by packing a refractory material, such as bonded and tempered molding sand, firmly about a *pattern* of the shape to be cast, the pattern being positioned and the sand mass being held in a removable rigid container—the *flask,* which ordinarily consists of an upper and a lower part—the *cope* and *drag* respectively, though occasionally for very intricate patterns an intermediate third unit, or *cheek,* may be necessary. After the sand mass has been compacted, the pattern must be removed or

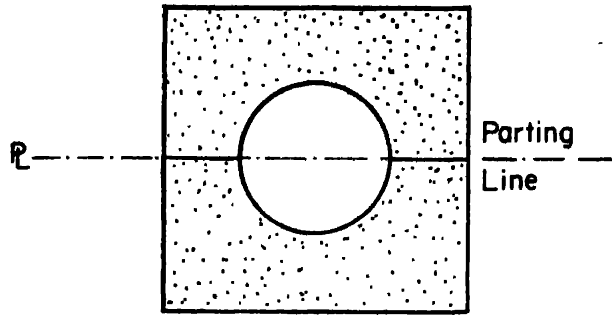


Fig. 1. **The simplest parting line is that illustrated here — a plane cutting through the equator of a sphere, permitting the pattern to be drawn from the sand without injury to the mold cavity.**

drawn. Nearly all patterns are made for a two-part mold, the sections of which meet at what is known as the *parting line* of the pattern. The simplest parting line is obtained when the halves of the mold meet in a flat or plane surface cutting horizontally through the pattern at its largest dimension. On a sphere, for example, such a parting line would be at the "equator," as in Fig. 1. In a two-part mold, with the parting line thus located, the pattern can be freed without tearing any part of the mold.

Once the pattern has been removed, the two halves of the mold are reassembled, forming the mold cavity. Molten white iron flows into this cavity through a *gating system.* This consists of a vertical opening—the *sprue,* horizontal channels—the *runners,* and entry passages—the *gates,* which lead into the cavity. Since molten iron contracts as it cools and solidifies in the cavity, reservoirs—*feeders*—are connected to the casting cavity at strategic points to supply additional molten metal to the parts of the casting that solidify last, in order to prevent the development of voids or internal shrinkage. Where openings, such as channels or interior holes, are designed in the casting itself, they are produced by the insertion into the mold cavity of properly shaped sand elements, baked or otherwise hardened, known as *cores,* which confine the metal to areas required by the design.

Good design, then, involves considerations of both the metal and the mold. These will be best taken care of if there is close cooperation between the design engineer and the foundry engineer throughout the development of the design and continuing through the approval of sample castings for production. This joint effort will make sure that the pattern which shapes the mold cavity will be an efficient foundry tool. Gating and feeding provisions will be such as to assure that an ample supply of molten metal will reach all parts of the mold cavity. The parting line of the pattern will be free of any unnecessary complication. Proper pattern draft—the tapering of the parts of the pattern vertical to the parting line —will be sufficient to secure clean separation of the pattern from the molding material so as to leave a sound, true mold cavity.

By consultation during the designing stages, the foundryman can help the designer in determining what malleable iron is best suited to the proposed use; in handling structural details of the design so as to facilitate casting; and in so planning molding and machining practice as to give proper consideration to parting lines, gating areas, locating points, and critical dimensions. The foundryman's suggestions may include the use of generous fillets or ribbing, the proper use of cores, and the casting tolerances which can economically be maintained on a particular design. He can recommend details in design to meet the requirements of a particular type of pattern equipment that will save time or money. He may have valuable recommendations for the subsequent machining of the castings. From such collaboration may be expected the production of well-designed castings that will more evenly resist the stresses in field use and will more satisfactorily meet service requirements with lower unit cost.

Since one of the advantages of malleable iron is its relative freedom from design restrictions, the parties interested in the casting design concept can arrange even a very complex part for satisfactory and economical production. Casting is a highly efficient use of metal, since castings are made from molten metal which will flow readily into intricate shapes that are exacting and time-consuming to produce by other processes. The contrast between a fabrication involving six individual parts and a one-piece malleable casting is clearly shown in Fig. 2.

From a strength standpoint, malleable iron offers the designer a high ratio of yield to tensile strength—65 per cent or better. This fact combined with the high fluidity of the metal when cast makes possible the use of light sections. Malleable is not section-sensitive, and therefore, with proper blending and filleting, light and heavy sections may be effectively

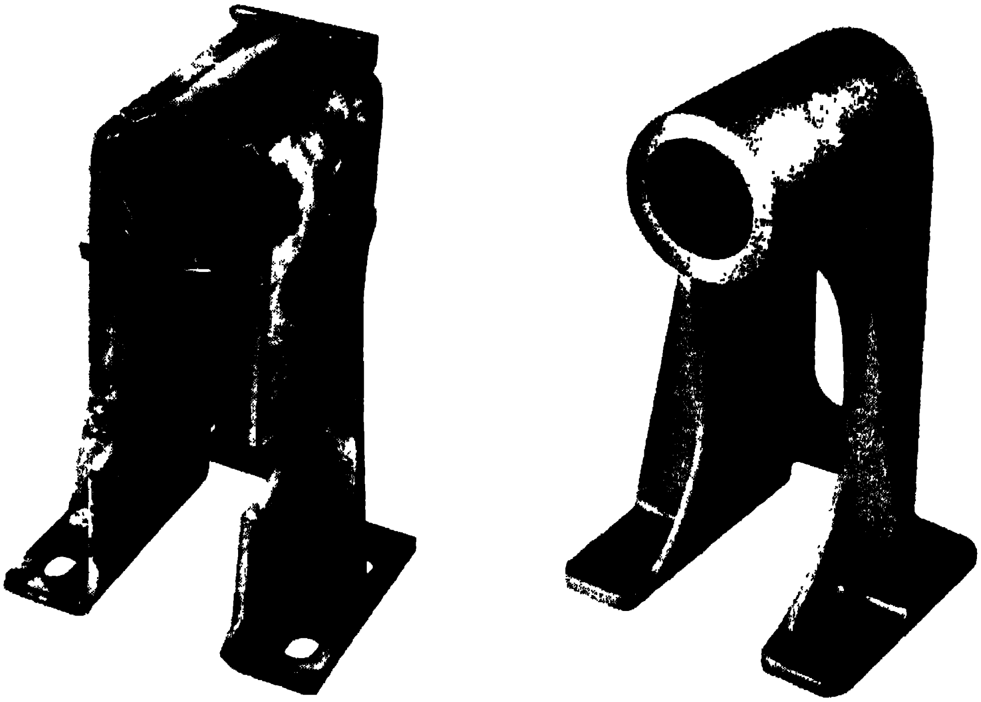


Fig. 2. To improve appearance, reduce cost, and retain or increase strength and toughness was the problem posed in the redesign of this elevator safety device. Conversion from a fabrication (left) weighing 22.15 pounds to a single clean-lined malleable iron casting (right) weighing 16.30 pounds was the solution.

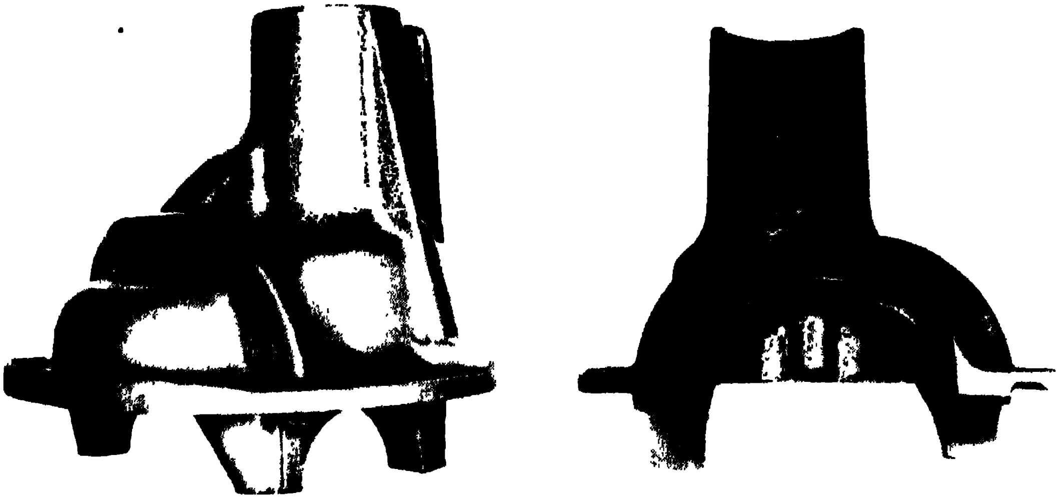


Fig. 3. **This differential gear housing shown in a full view and sectioned, weighing some 20 pounds, illustrates the design versatility of malleable iron.**

combined in one casting. For example, as Fig. 3 shows, a differential gear housing weighing some 20 pounds may have bearing seat sections which incorporate a $1\frac{1}{4}$-inch cube of metal, but some of its wall sections and ribs, with proper blending, may be not over $\frac{1}{4}$-inch in thickness. In this same part, the channel through which the oil must return can be cast by means of a core.

Experimental stress analysis may be used to advantage in developing designs for malleable iron castings. Sample castings may be made from the master pattern and checked by stress analysis to determine whether further changes are needed before production pattern equipment is prepared. Any or all of the conventional tools—brittle lacquer, strain gages, and photo-elasticity—may be employed. Stress analysis gives the designer a means of creating a casting equally balanced throughout in stress when put under field loading. Such stress balance may provide a lighter casting of the same strength by removing excess metal in low-stressed areas, or may increase the casting's strength greatly by proper distribution of the metal without increasing the weight.

True for malleable iron castings as well as for most other products is the general principle that pleasing appearance is basic to good design. Of equal significance, however, are several specific principles which apply directly to the design of castings and several particular requirements involved in the design, selection, and use of patterns. In following sections, this chapter will discuss these matters in order. The basic design principles will be taken up first:

BASIC DESIGN PRINCIPLES

1. Make Proper Use of Fillets and Round Corners

Use of fillets and radii to avoid sharp corners is very important in the design of malleable iron castings. Both casting and service factors con-

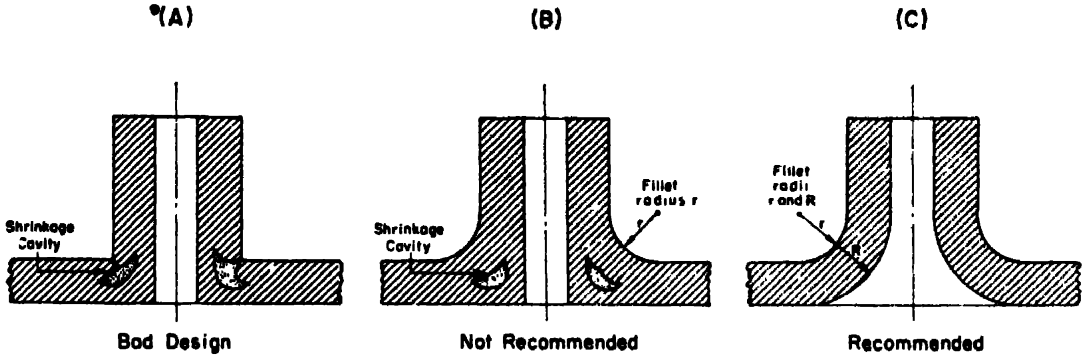


Fig. 4. **(A) Bad design, in which an unfavorable stress pattern develops and a shrinkage cavity forms because of the sharp corners. (B) Not recommended; the exterior fillet creates a large mass of metal which cools slowly and may form a shrinkage cavity because it is inadequately fed. (C) Recommended design, in which proper filleting insures against stress concentration and promotes shrink-free solidification in the corners.**

tribute to this importance. The basic production reason foundrymen use filleting is that a casting radiates heat at right angles to its surfaces, and a concentration of heat develops at any sharp inside corner during solidification. This concentration of heat causes a hot spot, that is, an area within the casting where a high temperature is maintained for a period of time. This condition is illustrated in Fig. 4A. Accompanying the concentration of heat is a localized concentration of stress, which follows a line extending across the cross-section of the casting if the heat concentration is high enough. If this stress exceeds the strength of the material—as it easily may since the metal is weak immediately after solidification—a heat check or hot tear may form. Fig. 4B shows a modification of the first design to which a fillet has been added at the hub to permit more uniform cooling of the exterior surface. However, in this case the fillet creates a heavy section, and the large mass of metal behind the interior angle promotes unfavorable thermal and stress concentration conditions.

In cases where fillets create heavy sections, wherever practicable, metal should be removed from the outer corner. This practice has the advantage of avoiding heat and stress concentration and possible internal shrinkage, which would have to be averted by the provision of extra feed metal from a feeder, and prevents a slight weight increase due to the metal added in the exterior fillet. Fig. 4C illustrates the recommended practice for filleting a casting.

The basic service reason for proper filleting is to avoid failure due to fatigue or to shock, both of which tend to produce cracks in sharp corners in metal. A competent design engineer would at once reject a design for a straight shaft of varying sections, whether cast or machined, if it called for sharp corners at the junctions of different sections, even though the shaft was to be only moderately stressed. Rejection would be caused by his knowledge that unless the sections of the shaft were blended by generous fillets, failures would probably occur because of cracks starting in the sharp corners due to fatigue or shock, and eventually being propagated. The same reason should rule in the design of malleable iron castings, which are often highly stressed.

2. PROVIDE FOR SOUNDNESS IN CASTINGS THROUGH PROPER SECTION DESIGN.

As a general rule it will be found that a metal thickness of 3/16 or 1/4-inch, with properly designed and located strengthening ribs, is extremely practical in work with malleable iron. Malleable castings may be produced in very light sections, as thin as 1/16-inch, or in sections as heavy as two inches or more. The thinness that can effectively be achieved depends in part on the design and size of the casting and on the pattern equipment.

Absolutely uniform section cannot be maintained throughout any but an extremely simple casting. Hence in practice the rule "seek uniformity of section" is expressed in two principles:

1. Keep the metal section as uniform as practicable.
2. Blend junctions of sections of different thickness as gradually as possible.

Application of these two principles in design will produce a casting of superior efficiency and life in service in the field, just as it will facilitate production of the casting in the foundry. The foundry logic underlying these principles of blending or tapering is based on what happens in a mold cavity that has been filled with any molten metal. Heat flows from the metal to the mold, so that the coldest metal is at the interface where mold and metal meet. It is at this interface that the first solid metal is developed.[104] As the liquid cools, the layer grows thicker, solidification progressing inward toward the thermal center of the mass at about the same rate, until the entire mass is solid. The growth of solid from the surface to the interior is gradual or progressive in nature.

Since the solidification rate is virtually constant, the thinner of two unequal joining sections will solidify in less time than the thicker. Differences in the mass and consequently in the solidification time of joining sections are important because white iron like all other ferrous metals contracts or shrinks in size during the cooling period immediately following solidification. The thinner of two joining sections will have solidified completely and will be in the process of cooling and therefore contracting while the massive section is still solidifying. A drawing action will result where the thin and thick sections join and will set up stresses that seek out the weakest spot in the piece, in all probability the spot where the contrasting sections meet. If the stress thus set up is greater than the low strength of the material immediately after solidification, a crack or tear will result.

A convenient method of determining, during the design stages, where substantial differences in mass may occur and where care should be taken to avoid cracks or tears, is the use of inscribed circles. The ratio of the mass of metal at one place in a section to that at another place in the section is the same as the ratio of the circles that can be inscribed at these places in the section. The method of inscribed circles, which is illustrated in Fig. 5, enables the designer to see in advance what the effect of differences in mass may be in the ultimate casting, and to adjust his design accordingly. As Fig 5 indicates, the method is of direct value in the designing of L-, T-, Y-, and X-sections in such a manner as to avoid the danger of hot spots and consequent shrinkage cavities or tears.

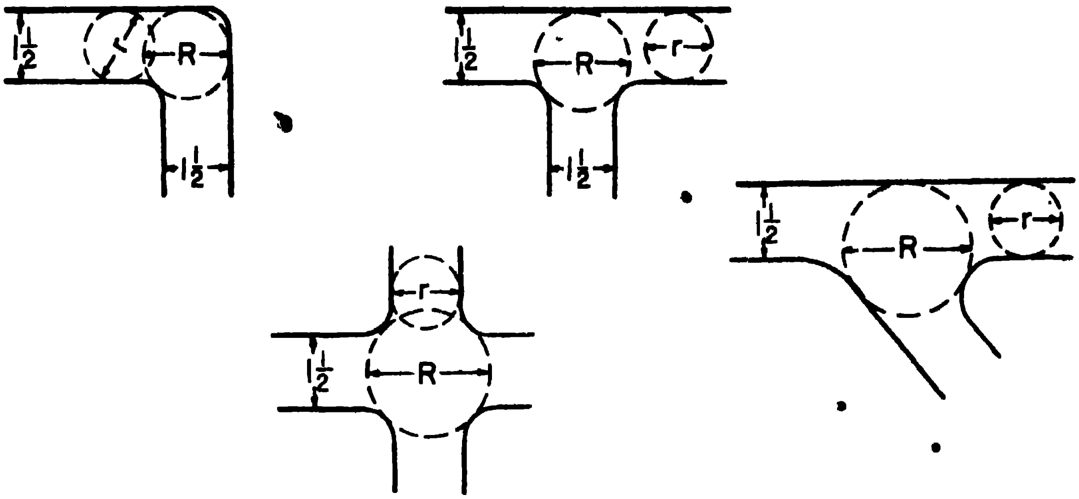


Fig. 5. **Use of inscribed circles to determine the effect of mass in the design of a casting.**

In essence, it is necessary, where unequal masses are involved, to blend from the larger to the smaller—from the thick to the thin section—as gradually as is practicable. This tapering distributes the stresses and disperses their concentration, thereby removing the tendency toward cracking. The outlines shown in Fig. 6 can be used as a guide when a design requires section changes.

The working application of these principles is embodied in Figs. 7, 8, 9, and 10. These charts show recommended fillet sizes as well as suggested design practice to be followed when sections of different thickness must be joined. Figure 7 shows a procedure advisable when a flange *B* is not more than 1.66 times as thick as its supporting wall *A*. The value of *R* is obtained from the graph in Fig. 9.

Figure 8 illustrates the corresponding procedure to be followed in joining walls approximately at right angles to each other. The walls shown are of usual thickness. For the construction indicated in Fig. 8 to be practicable, *B* should not exceed 1.66 times *A*. Values of *R* for this application are also determined from Fig. 9.

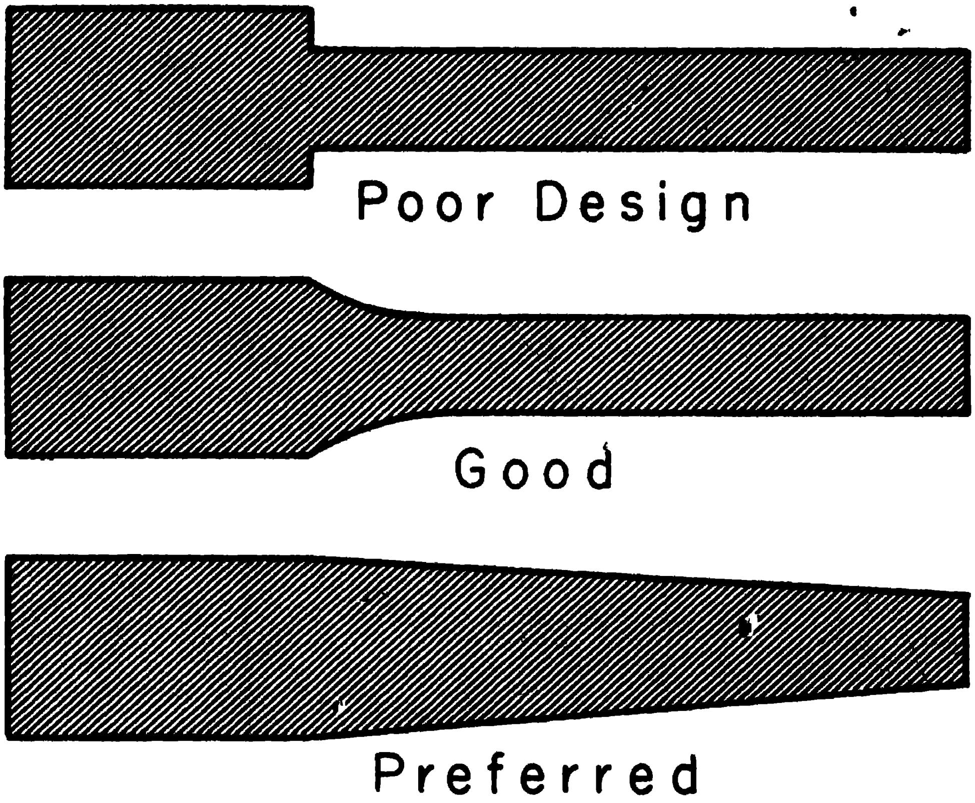


Fig. 6. Tapering to join sections of different thickness in order to prevent concentration of stress and to promote directional solidification.

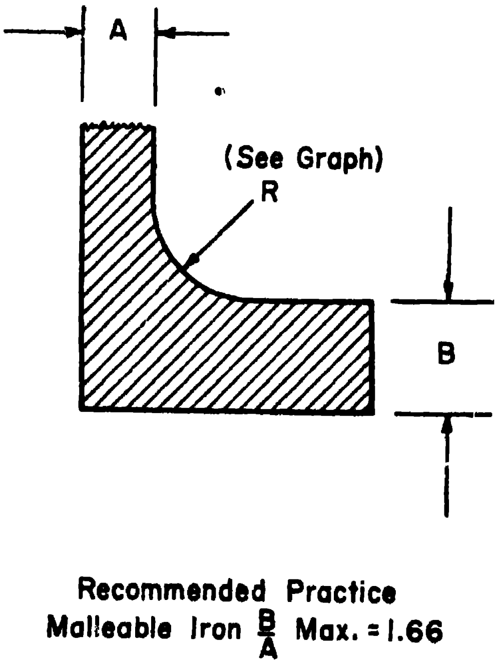


Fig. 7. Recommended filleting procedure when the flange B is not more than 1.66 times as thick as the supporting wall A.

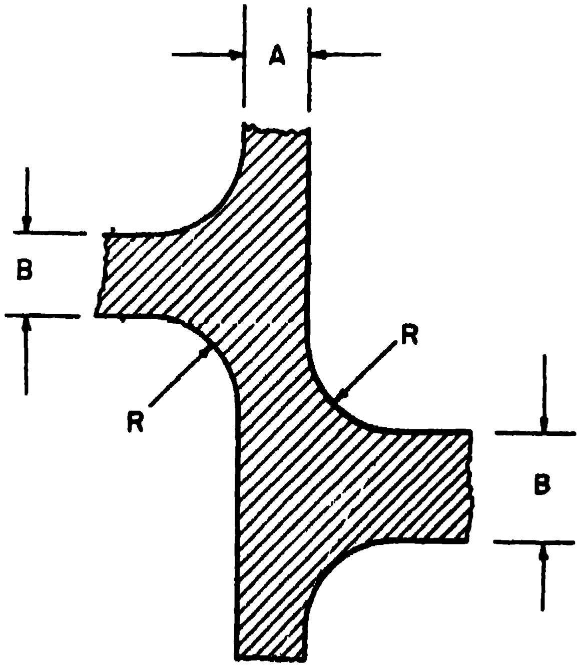


Fig. 8. Recommended filleting procedure for joining walls approximately at right angles to each other.

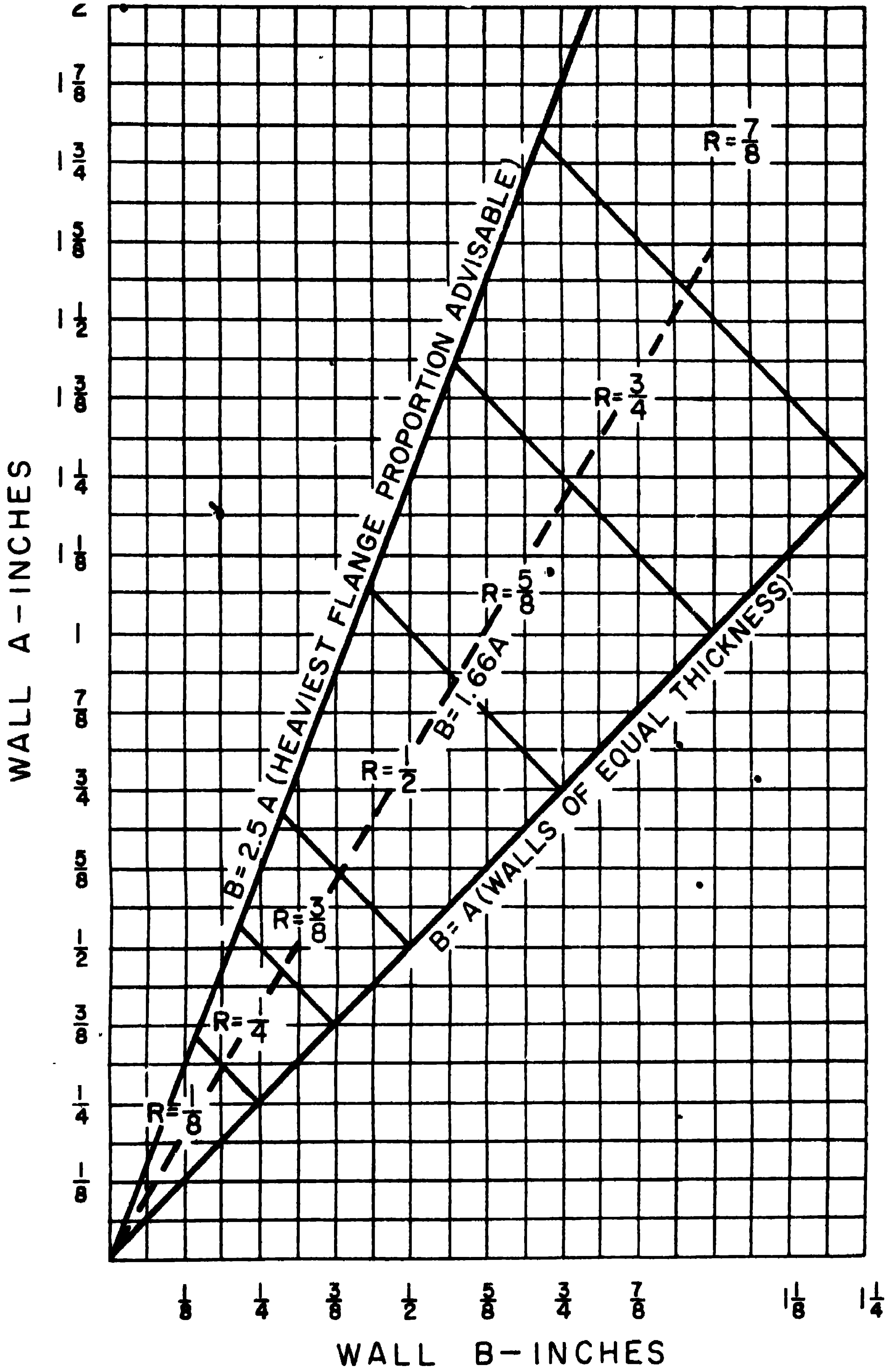


Fig. 9. Recommended fillet radius to be used in casting design for all joints with walls at right angles to each other and for walls of all usual thicknesses and combinations of thicknesses.

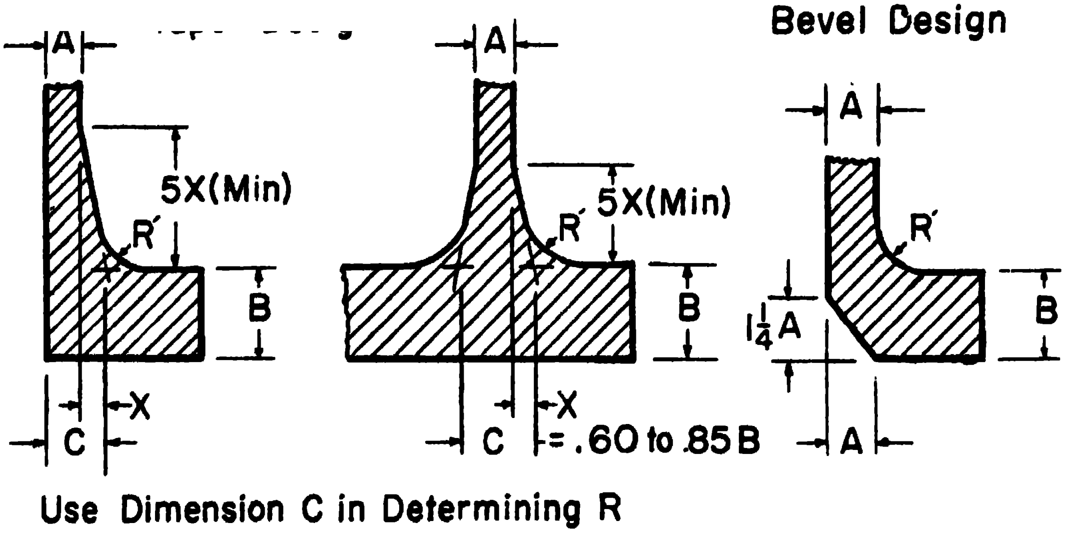


Fig. 10. **Recommended filleting procedure when the flange B is more than 1.66 times as great as the supporting wall A.**

When *B* is more than 1.66 times as great as *A*, a bevel or taper design such as that illustrated in Fig. 10 should be used, since it assures proper blending of sections. The value of *R* for this application is also determined from Fig. 9.

Contraction may also be the cause of difficulties when massive sections are involved. As the molten metal in such a section solidifies, the solid layer at the outside of the mass forms a shell, the wall thickness of which increases as additional metal solidifies. The shell tends to hold its shape, and hence to pull molten metal toward the outer walls from the center. The last bit of liquid near the center of the mass may therefore not be of sufficient volume to fill the remaining space, so that when it solidifies a partial void or porous spot (shrinkage) will be left in the center of the mass. Such porous spots are avoided by feeding molten metal into the heavy section to replace that which is drawn out by the outer layer during solidification.

For the reasons which have been suggested above, the combination of a substantial boss surrounded by a thin plate section may present a problem, Fig. 11A. When such a casting is designed, consideration can be given to removing the heart of the mass by using a core and thus obtaining a more nearly uniform metal section. The boss can be cored in either of two ways, depending upon the metal section involved and upon the purpose of the finished hole. If bearing throughout the boss is necessary, the coring illustrated in Fig. 11B must be used. The coring shown in Fig. 11C is practicable for other designs.

Certain wheels also illustrate the design principle under discussion here. The rim and hub must usually be heavier in section than the spokes of an open wheel such as a hand wheel, or than the web in a solid wheel.

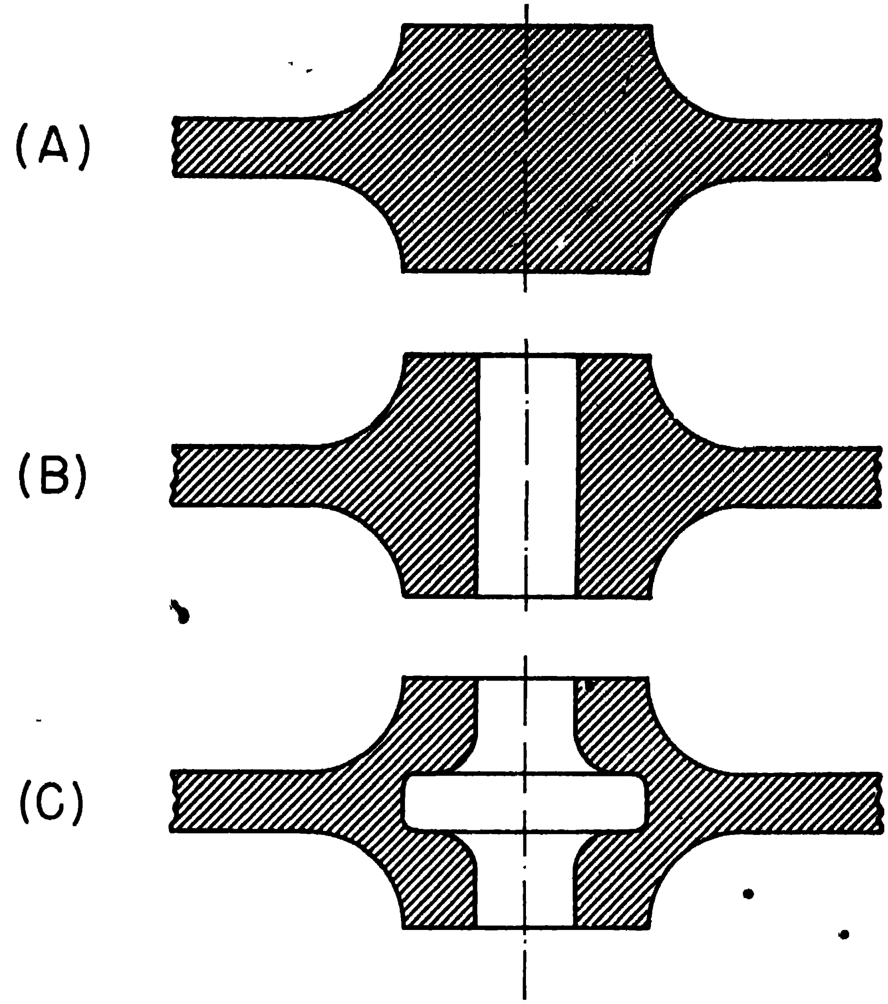


Fig. 11. **(A) Original design of a heavy boss connected to a thin plate.**
(B) Coring to give somewhat improved metal section when a boss and a thin plate section must be combined, and bearing throughout the boss is necessary.
(C) Coring practicable for substantially uniform metal section, when a boss and a thin plate section are combined but bearing throughout the boss is not essential.

The rim, hub, and spokes, or the rim, hub, and web may indeed each cool at a different rate because of the variation in their cross-sectional area, and considerable internal stress will thus be set up in the casting. Straight spokes, or a flat web, under these conditions might crack the hub or the rim. But if the designer plans the spokes to have a slight wave or curve—that is, to be somewhat S-shaped, as in the industrial truck wheel shown in Fig. 12—they will under stress tend to be pulled toward straightness, and the centralizing of stress which causes tearing will be avoided. The same can be said of a wheel if the web is designed to be dish-shaped rather than flat. Fig. 13 illustrates this point. These provisions give the different sections of the wheel enough flexibility to adjust themselves and to withstand the cooling strain without cracking.

It should be borne in mind that if any stresses remain in a white iron

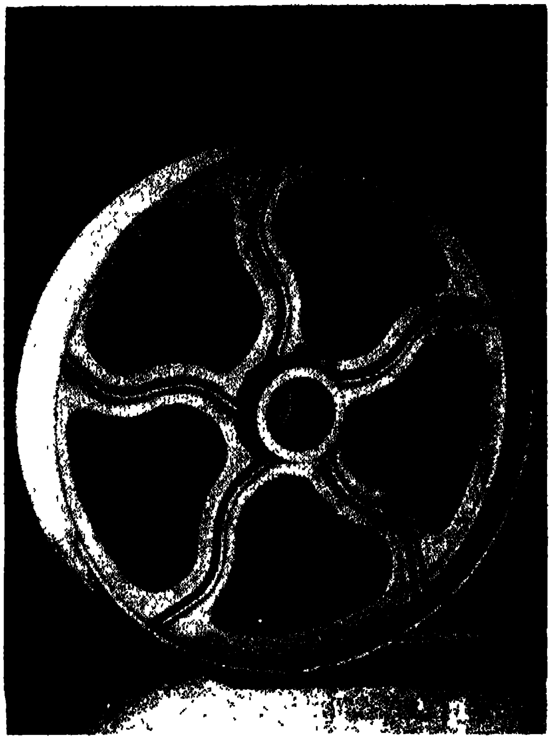


Fig. 12. This malleable iron industrial truck wheel, which replaced a composite fabrication, illustrates the S-shaped spokes which avert centralization of stress.

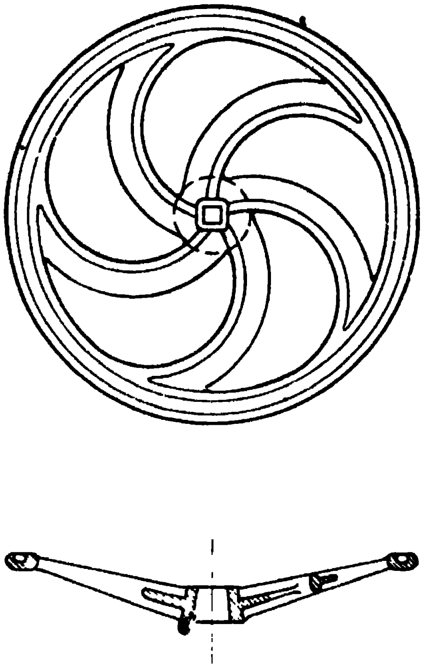


Fig. 13. In wheels with a web rather than spokes, the dished design shown above averts stress concentration. The use of an uneven number of spokes avoids directly opposed cooling stresses.

casting they will be eliminated by the heat-conversion process essential in the production of malleable iron. In this process the structure of the metal is completely changed from the original as-cast combined carbon constituent to the final tough, ductile ferrite containing nodules of temper carbon.

Careful attention to fundamentals is required, to insure soundness in castings, in deciding on the location and dimensions of the gate necessary to permit satisfactory feeding of metal through all sections of a casting. Figure 14 shows an original and a redesign dealing with this problem. In the original, the thin metal section around the boss was not sufficient for proper gating and feeding; in the redesign, the thin section was eliminated to permit gating and feeding directly into the boss. Another way of increasing the metal section to assure ample gating area is to extend bosses at their full width to the edge of the casting.

A related gating and feeding problem arises in the design of castings having a relatively thin flange surrounding a heavy hub. Since the metal must be fed to the hub in such castings, the flange may be thickened at some point or points by a pad or pads extending from the edge to the hub, as in Fig. 15. If possible, the design should permit retention of the pad, for removing it by grinding or machining will increase the cost of the casting. If balance is important, as in the case of a hub, a compensat-

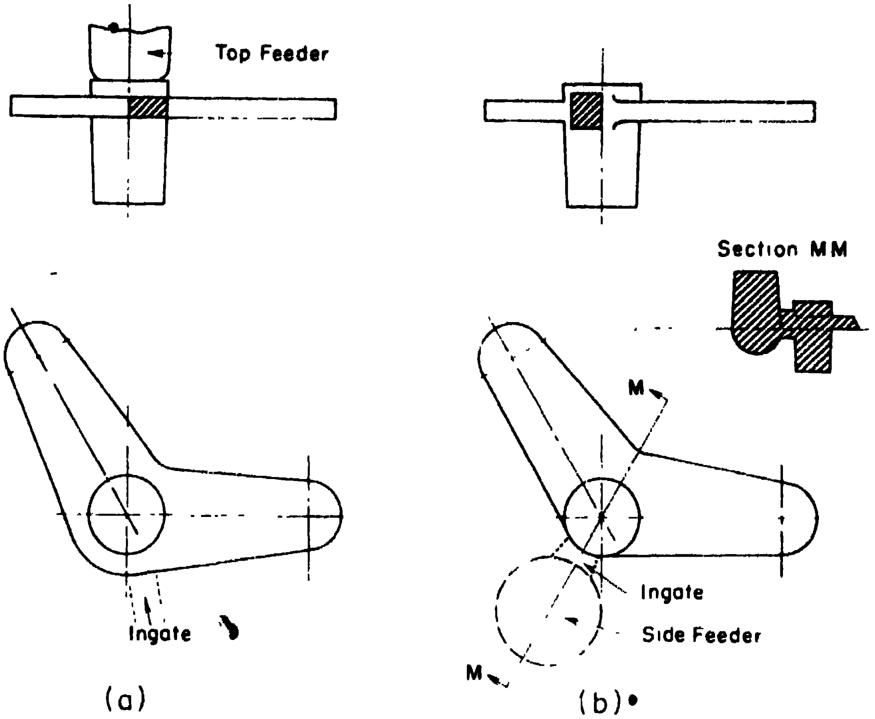


Fig. 14. **Drawing (not to scale) illustrating a design change to provide proper gating area. The thin flange on the casting at the left did not lend itself to good gating practice. This problem was eliminated by extending the boss to the edge of the casting as shown at the right.**

Fig. 15. **The redesigned flanges (top) show a built-up gating pad to assure an ample supply of metal to the hub. The gate on the flanges at the right (top and bottom) have been ground.**

ing pad may be placed diametrically opposite. The pad may usually be placed on either face of the flange.

In certain cases it may be necessary for the foundry to add a wedge of metal for feeding as shown in Fig. 16. This metal may later be removed by grinding or milling.

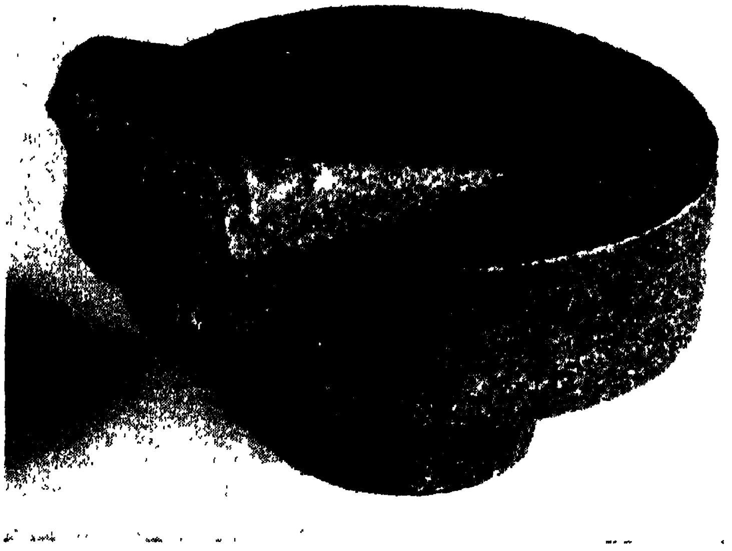


Fig. 16. **A wedge of metal has been added to facilitate feeding.**

Levers of many sizes and types are made of malleable iron, and they offer various special design problems, one of which is illustrated in Fig. 17. Here the pinch bolt boss has been filled out slightly, not only to permit better gating but also to simplify grinding. Grinding the gate off this casting to leave a flat finished shape is quicker and cheaper than attempting to obtain a rounded end. In view of the fact that the grinding operation on a small lever is often the most expensive single operation in the manufacture of the piece, design of the kind shown in Fig. 17 has distinct advantages. The revised type of gate may also be removed by shearing, thus eliminating grinding entirely.

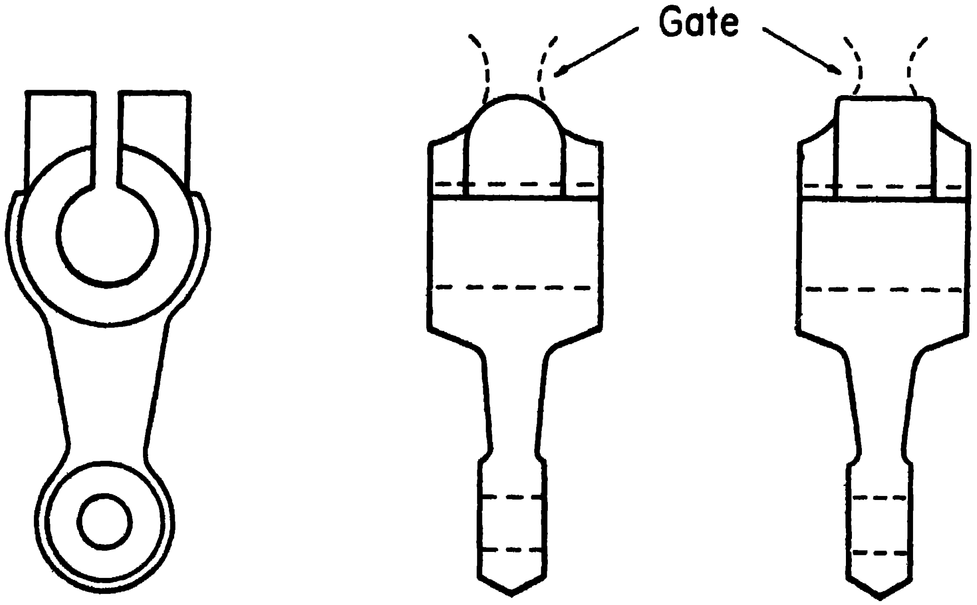


Fig. 17. **Lever, showing at right preferred design for gate removal.**

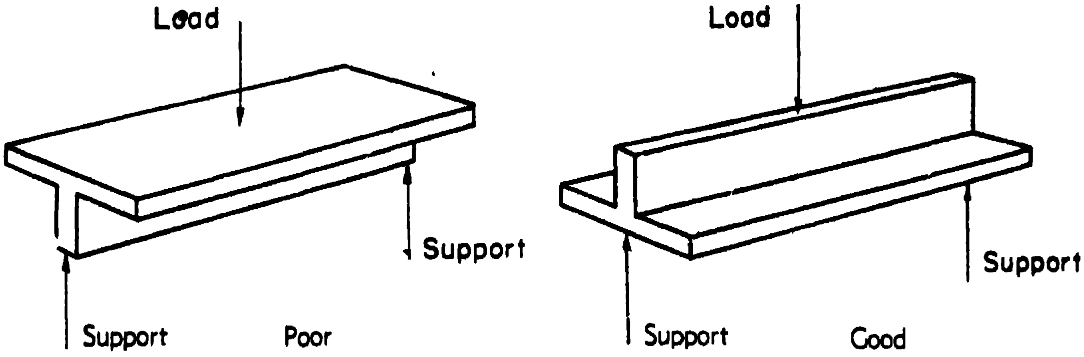


Fig. 18. **A piece with rib section in tension, left, and in compression, right.**

3. Keep Plates in Tension and Ribs in Compression.

Malleable iron castings in many applications are subject to high stresses in use and to severe shock loads. When designing for such an application, the engineer should bear in mind what may be called the "plates in tension, ribs in compression" rule. To visualize the necessity for it, consider what happens to a piece with its rib section in tension rather than compression, as shown at the left in Fig. 18.

Assume that the load is variable and pulsating and that at times severe impact or shock throws extreme stresses into the piece. These stresses will be greatest directly under the load point, at the bottom of the rib, and in the outer structure of the rib. Under extreme shock, when the stress exceeds the strength of the material, the rib is bound to crack or tear open. Though the tear may be very small at first, once it has been started, stress concentration at this point may cause it to progress. Turning the piece upside down as at the right in Fig. 18, putting the plate in tension and the rib in compression, greatly improves the design. Distributed over the plate, which is many times wider than the rib, the stress does not tend to concentrate in a very narrow metal section, and no tear starts. The grains of the metal in the rib will be properly in compression.

A practical application of this principle is presented in Fig. 19 showing the original and redesign of an axle clamping plate which fits under a truck axle and by means of U-bolts holds the axle up against a spring. Such a device is subjected to severe stresses in service. These were too much for the original design, shown at the left in the figure, which was essentially a single curved plate strengthened by four ribs. Failures starting in the ribs, where high tensile stresses in the outer fibers under the edges of the axle started small tears that progressed until the strength of the part was gone, necessitated redesign. Putting the ribs in compression and the plate in tension resulted in satisfactory performance. The three weep holes in the redesigned plate were cast in the piece.

Subsequently, through the application of experimental stress analysis, the designer could go one step further by eliminating the ribs altogether.

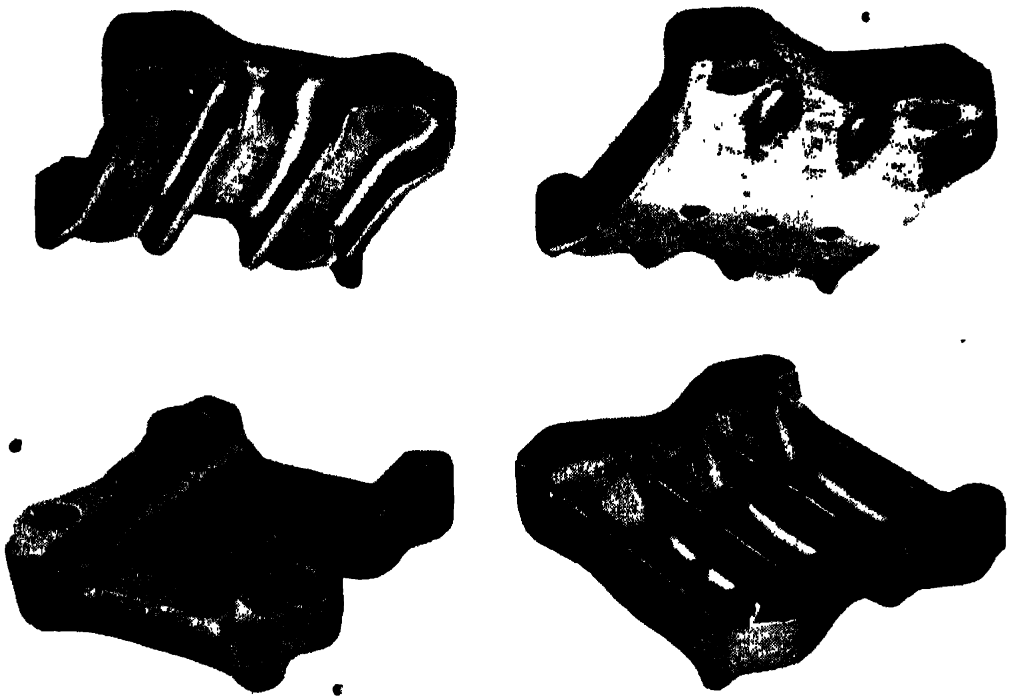


Fig. 19. **Upper and lower left, axle clamping plate as originally designed; upper and lower right, redesign.**

The resulting casting is lighter in weight, has more eye appeal, and is greatly simplified, yet structurally adequate. (See Fig. 20.)

In many cases, a casting can be strengthened by using corrugated sections with a uniform thickness of metal, thereby eliminating the foundry problems created by using ribs and plates forming "T" or "X" sections. This corrugated design also at times excels a rib-and-plate design in the reduction of high stress areas that occur on ribs especially

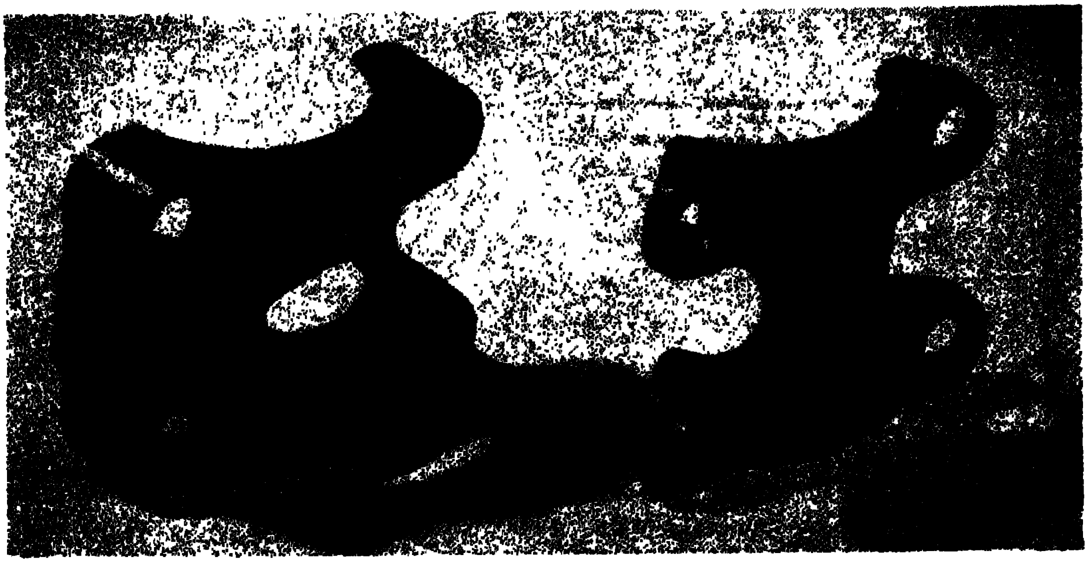


Fig. 20. **Axle clamping plate developed through the application of experimental stress analysis. Original casting left, and redesign right.**

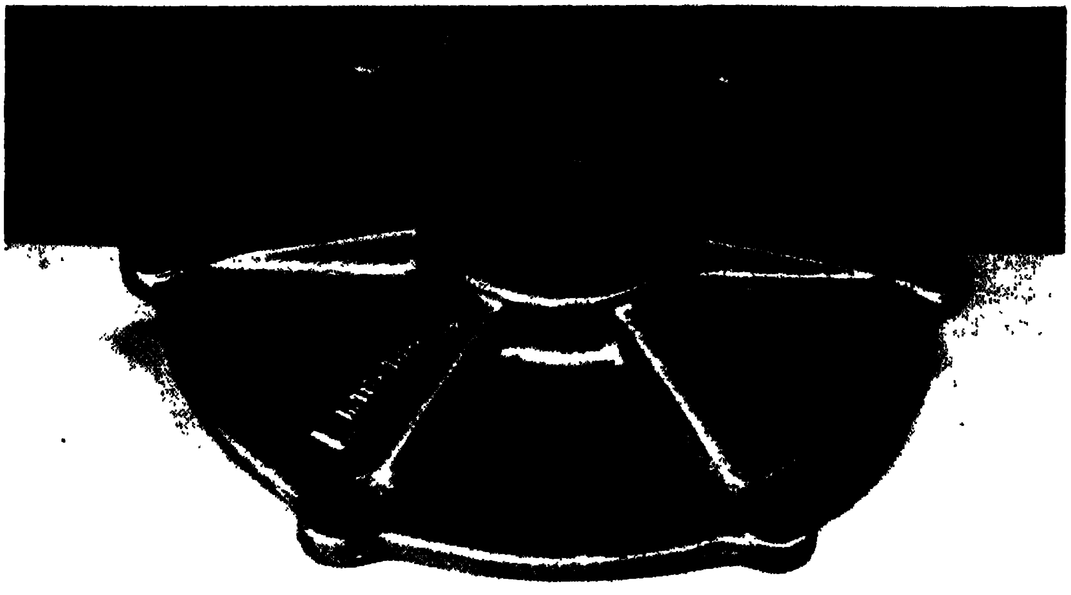


Fig. 21. **Casting incorporating flat plate with ribs blending out from the hub, subject to stress concentration where ribs join plate.**

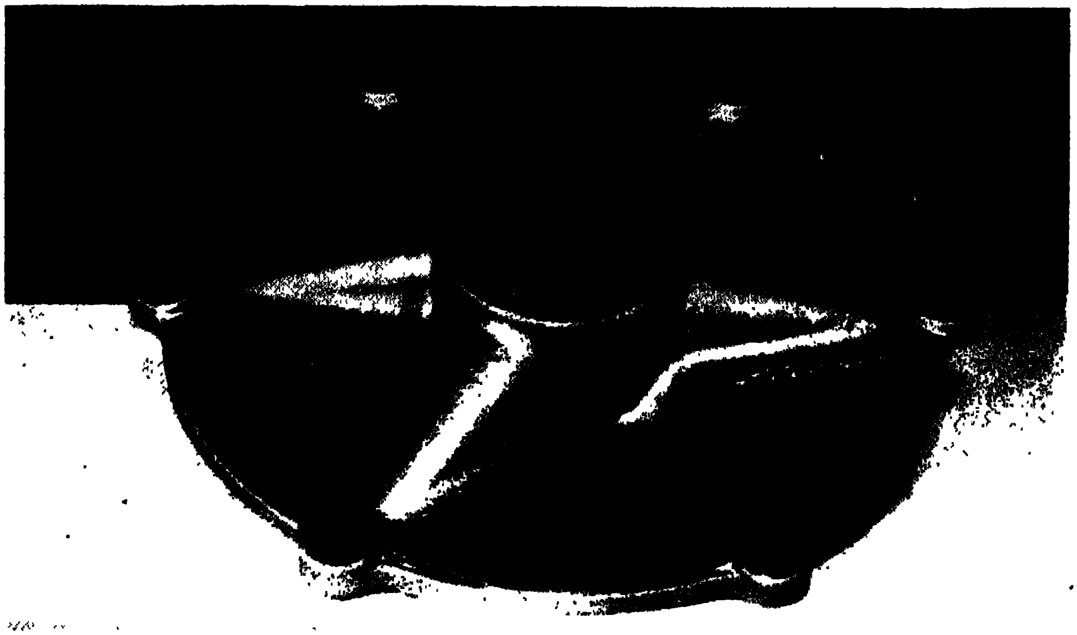


Fig. 22. **Casting redesigned to use a corrugated plate of uniform thickness to connect hub and outer section, securing more uniform stress distribution.**

when they are put in tension. An example is shown in Figs. 21 and 22. The casting in Fig. 21 is made up of a flat plate with opposed ribs blending out from the hub. This casting, as shown in Fig. 22 was changed to use a corrugated plate of uniform thickness to connect the center hub to the outer section, thus making it more uniformly stressed in service as well as eliminating the "hot spots" created where ribs joined the plate on the original design.

The three basic principles of design which have been discussed thus far—

1. Make proper use of fillets and round corners,
2. Provide for soundness in castings through proper section design,
3. Keep plates in tension and ribs in compression,

—are matters on which the design engineer and the foundry engineer can collaborate regardless of the specific casting procedures later to be followed. Their cooperation, however, can extend usefully still further, notably into the area of the design of patterns and the manufacturing processes best suited to the production of castings from those patterns. This chapter will next consider the use and importance of patterns.

PATTERN EQUIPMENT

For the production of good castings, the foundry must have adequate pattern equipment. The accuracy, the appearance, and the ultimate cost of castings depend largely upon the type, layout, and quality of the patterns. Rejections after machining, for example, are expensive, and they may be caused by faulty patterns. Foundryman and customer therefore share equally in their dependence upon pattern equipment and will benefit equally if careful analysis of foundry and production problems is made at the time new pattern equipment is being considered. Not only the design and shape of the castings and the size of the order, but also the production methods of the foundry must be taken into account in such analysis, for the foundryman must determine the type of pattern equipment best suited for the production requirements of each casting.

The customer's principal concern is that the pattern be precise so that the castings made in molds formed from it shall be accurate in dimension and sound in section. The foundryman's concern is the same. His is expressed, however, not only in terms of the pattern's adherence to the engineering design, but also in terms of the pattern's efficiency and usefulness as a working foundry tool. The customer looks to dimensions and contour; the foundryman looks to these and, in addition, to *gating, parting,* and *draft,* particularly as they affect molding technique. These three foundry problems are of vital interest to the customer as well, because they affect the ultimate cost and quality of the casting. These considerations taken together emphasize again the necessity, for the production of satisfactory castings, that designer and foundry engineer work closely together during the entire progress of the idea from drawing board to finished casting.

A major requirement in casting is to assure that a full supply of molten metal will properly reach all parts of the mold cavity. This requirement poses the first foundry problem—the provision of a suitable *gating* system. Whenever a number of patterns are assembled on a plate and attached to a gating system, the foundry must space and arrange them so as to permit sufficient molding sand to separate the individual pieces with a wall of adequate and economical strength. In addition, arrangement should permit proper gating and feeding of the individual patterns.

Another foundry problem is that posed by the parting line of the pattern. The simpler this is, the more economical and efficient will the molding process be. A horizontal plane passing through the pattern at its largest dimension is the most desirable. The largest dimensions of some castings often are not in a single plane, so that the parting surfaces are irregular in profile. By proper design, however, the simple two-part mold can generally be used in the production of such castings. But when projecting flanges, ribs, or similar elements complicate the parting profile, the foundry may have to resort to the use of cores or special equipment. These tend to increase the cost of producing the castings. Simplification of parting line design thus directly affects not only the cost of pattern equipment but also the cost of the resulting castings.

Drawing a pattern from the sand still may offer some difficulty even though the pattern has been so designed that a satisfactory parting line is obtained. Pattern draft—the tapering of those parts of the pattern which will be in a position vertical to the parting line as the pattern is lifted from the mold—supplemented usually by a mechanical vibrating operation aids the ready freeing of the pattern from the sand.

How a modern foundry goes about the preparation of pattern equipment for the production of commercial castings is shown in thumbnail fashion in Figs. 23-29 which occupy the following four pages. The equipment shown is used for the manufacture of one specific casting. Operational details in producing and using it will vary from foundry to foundry. The figures that follow, however, are representative of accepted present-day practice.

The foundry should specify the type of pattern equipment which will not only meet its production requirements, but at the same time insure the lowest cost of castings to the customer. In evaluating the various types, however, the customer does well to remember that with pattern equipment as with many other tools, a somewhat larger first cost is often more than justified by the gains in economy and quality which it produces.

Malleable casting producers maintain their own pattern shops or are in close contact with satisfactory shops which specialize in production patterns, and whenever new pattern equipment is required, it is advisable that the order for it be placed with the foundry which is to make the castings. Pattern equipment then will fit the particular needs of the producing foundry, which thus can more readily assume responsibility not only for the dependability of the patterns but also for the accuracy and soundness of the castings to be produced from them. All foundries prefer to gate patterns which they are to use, because by so doing they are able to allow for their own particular practices. Generally, the foundry makes sample castings from the master or loose pattern in order to determine the size of the gate connections and feeders necessary to insure satisfactory castings. The pattern equipment is then gated in accordance with these findings.

However, if a customer decides to furnish his own pattern equipment, it is essential that he consult the foundry regarding type of equipment, shrinkage allowance, finish allowance, size tolerances, arrangements for required draft of pattern, parting line, the method of molding, and in the case of machine molding pattern equipment, the size of flasks and plates and layout for the exact location of patterns on the plates. If the gating is to be done by other than the foundry, the foundry's directions as to layout are especially important; they should specify the exact size of feeders and the arrangement of gating, together with the spacing of patterns.

Growing out of the preceding general discussion of foundry problems concerned with patterns, several basic foundry-design principles can be stated as follows:

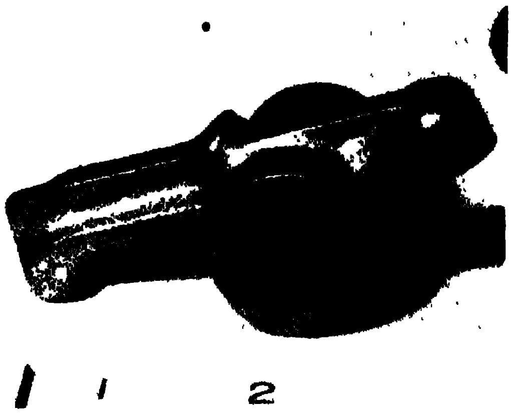


Fig. 23. The pearlitic malleable iron automotive rocker arm casting shown here is the one produced from the pattern equipment illustrated in the following figures. The relative size of the pattern equipment may be gauged from the size of the casting. The cored hole cast in the piece should be noted.

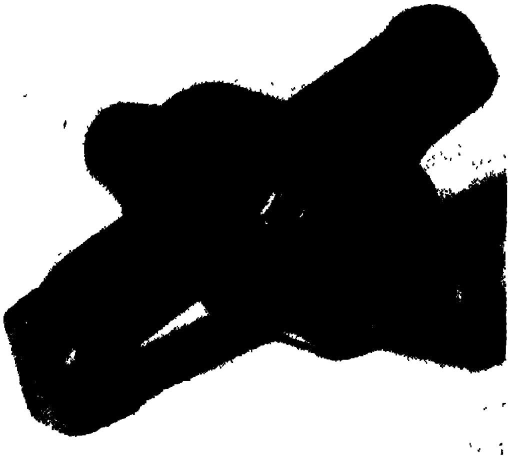


Fig. 24. An expertly made wood master pattern for the rocker arm produced to exacting tolerances under direct consultation with the foundry engineers is the first step toward the production of quality castings. Contraction or shrinkage allowances for the metal master pattern, working pattern, and the casting have been incorporated in the wood master pattern dimension. The projecting tapering elements are core prints to position the core in the mold.

Fig. 25. After the wood master pattern has been checked dimensionally sample molds are made to determine the correct shape and size of feeders for the most economical casting production. An assembly of metal master patterns to be used in making the production pattern equipment is then fabricated. If required, sample castings can be produced from this metal master pattern assembly for use as a guide in setting up various tooling requirements.

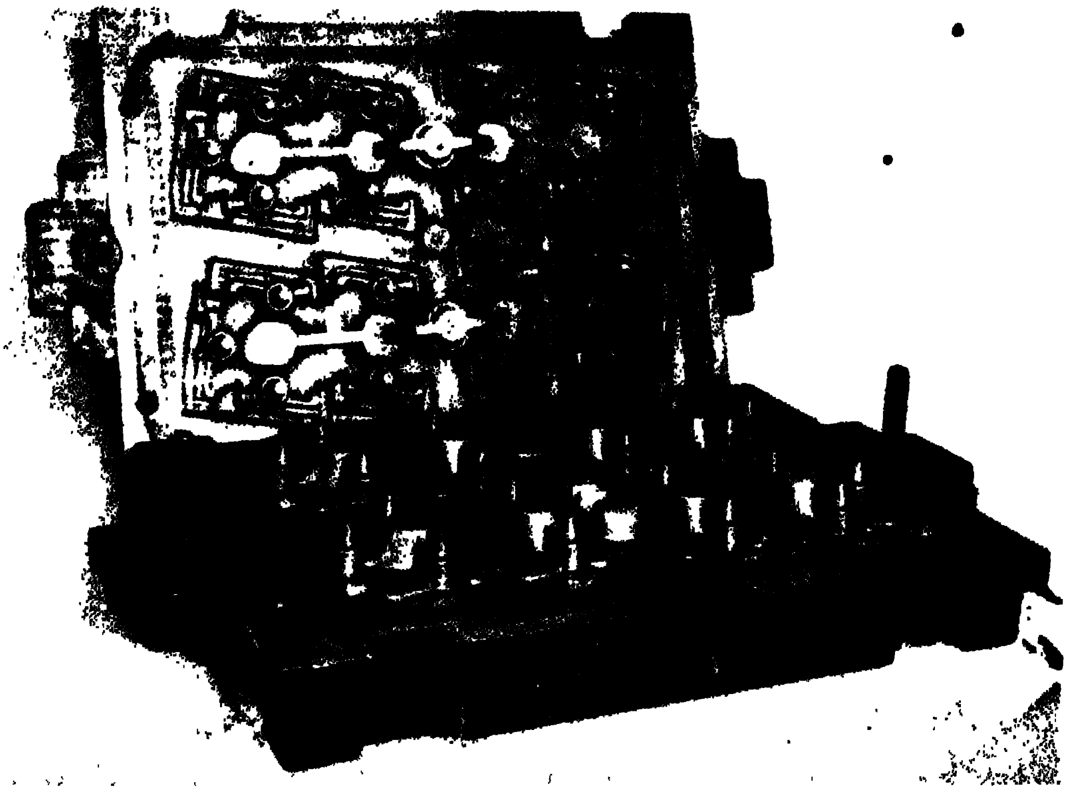


Fig. 26. This is a cope and drag pattern, used for larger production requirements. For greater accuracy, the individual patterns may be machined before being inserted or mounted in the assembly.

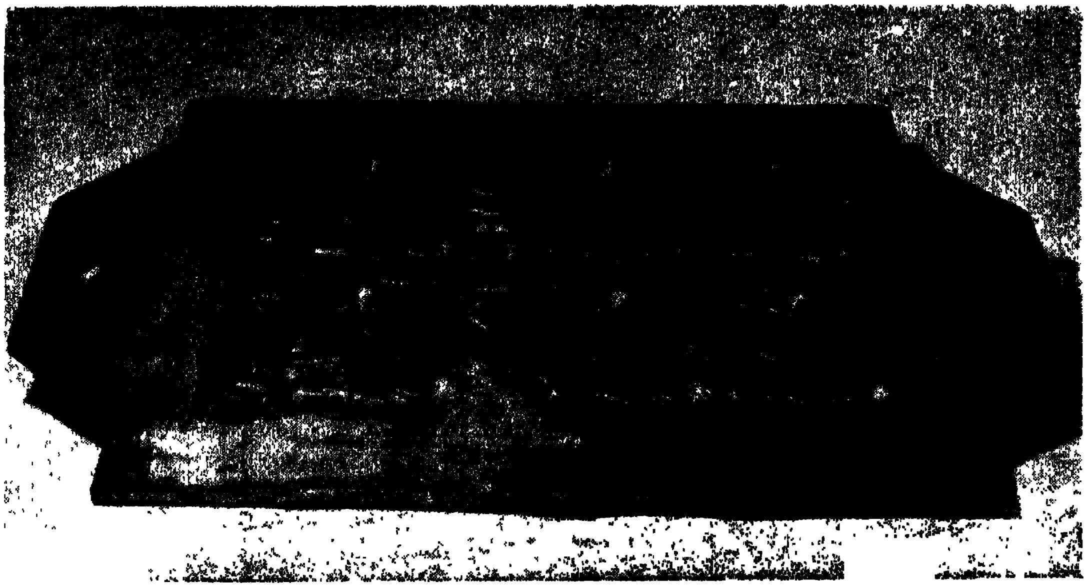


Fig. 27. The matchplate pattern—shown here, as made in aluminum—is the cheapest and fastest to produce and is used primarily for production of castings in low to moderate volume.

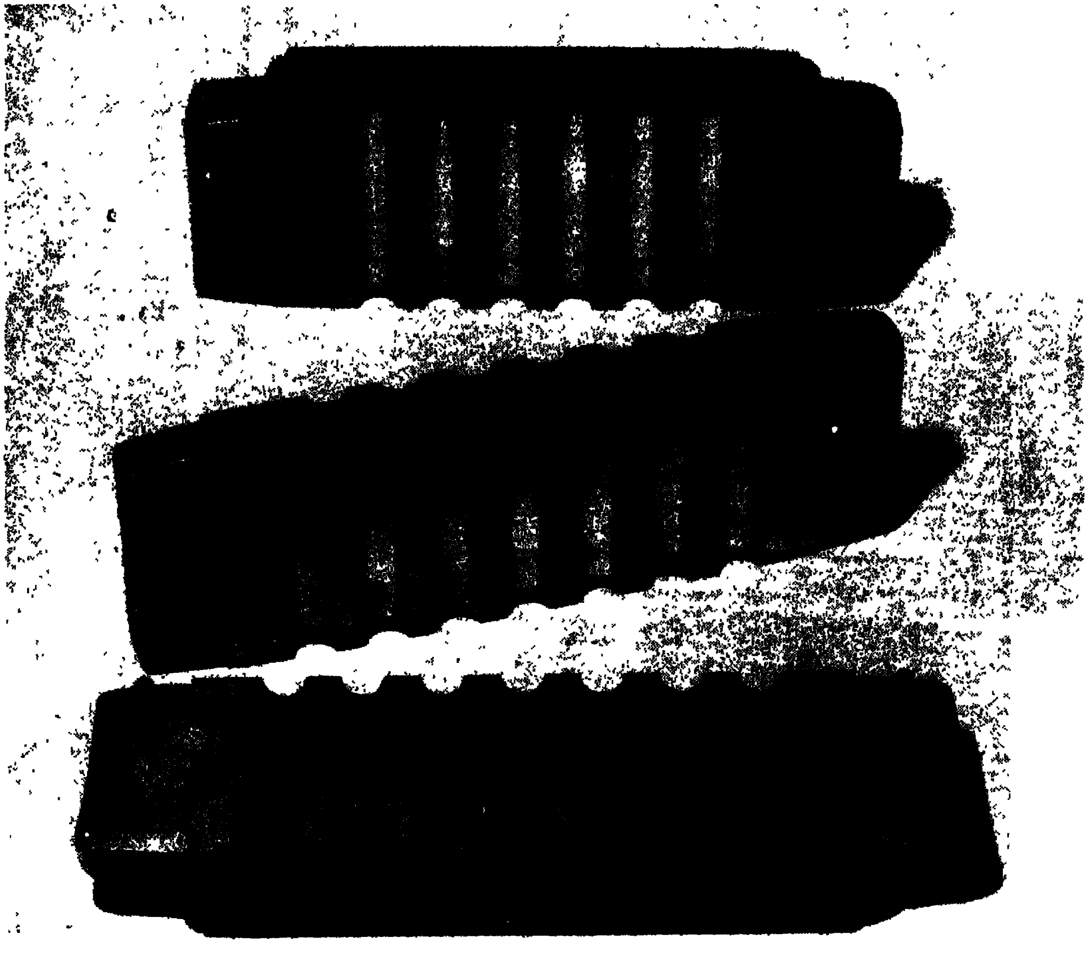


Fig. 28. The vertical aluminum blower pin core box shown is of the type used where the diameter of the core is large enough to stand on end while being baked. The type of blower core machines used by the foundry influences the type of core box selected.

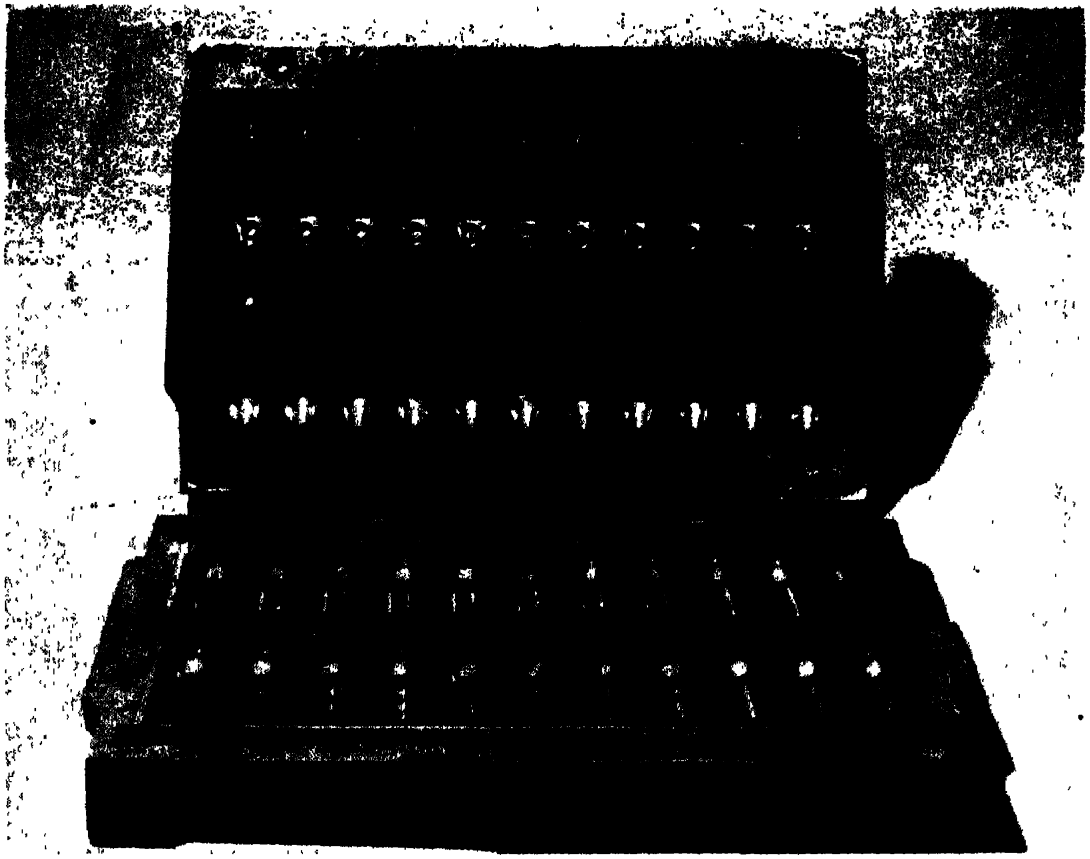


Fig. 29. A draw-type core blower machine is required to produce cores from the horizontal aluminum blower pin core box shown here. Core driers are required since the core diameter is too small to allow the cores to stand on end while being baked. In some cases, however, the drier may serve as the lower half of the core box, then being known as a blow-in drier. The blow nozzles and vents are visible in the box shown. Very accurate cores can be made from this type of equipment.

1. Allow Sufficient Draft.

When the cope half of the mold is lifted from a pattern or the pattern is drawn from the drag half, there will obviously be trouble if the diameter of a vertically cast cylinder is greater at its extreme ends of the mold than its diameter at the parting line of the two mold halves, as in Fig. 30. If such a condition exists, the larger diameter pattern ends, when being withdrawn from the mold, clearly will tear up the sand and destroy the imprint which had existed prior to the attempt to remove the pattern. It is also impractical to draw a vertically molded cylinder or other pattern which has exactly the same diameter or thickness deep in the mold as it has at the parting line. Accordingly, it is standard practice to add a slight angle of taper commonly known as a draft—generally one to two degrees —to the vertical sections of the pattern. Thus the pattern comes easily from the mold, and the resultant castings are duplicates of it.

To prevent destroying the imprint when the pattern is withdrawn from the sand mold and to facilitate drawing the box from the core, a small amount of draft is required in both the pattern and core box.

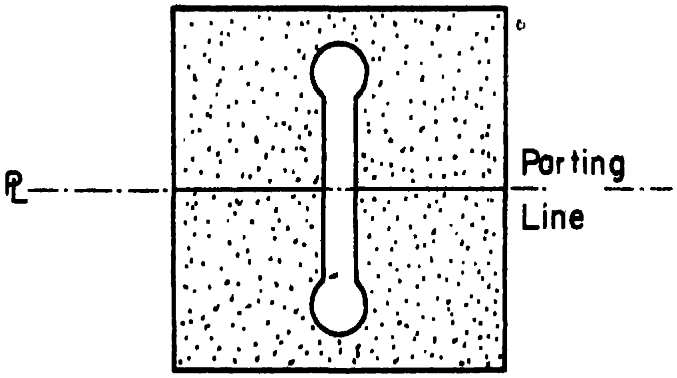


Fig. 30. **Diagram showing schematically and exaggeratedly a pattern impossible to draw successfully from the mold.**

For both patterns and cores it is standard foundry practice to add the draft to the dimensions specified on the drawings, unless the customer indicates otherwise. Hence it is imperative that the customer and the foundry make sure in the beginning that either maximum or minimum dimensions are specified on the drawings from which original patterns are to be made, and that is is clear whether draft is to be added to or subtracted from the dimensions given in the drawings. Unless such specification is clearly made, the foundry, following standard practice, will add draft to given dimensions. Control of this problem in advance is to the customer's economic advantage, since minimum draft results in weight reduction and less machining once the castings have been made. For production patterns, draft will generally amount to one or two degrees, as compared with the seven degrees generally required for forgings.[105] Liberal draft produces the smoothest casting surface and should be used whenever possible. If a minimum of taper is required, it should be specified; when liberal draft can be used, it should be noted. In establishing and applying draft allowance, consultation between user and producer works to the best interests of both. Figure 31 illustrates the use of draft.

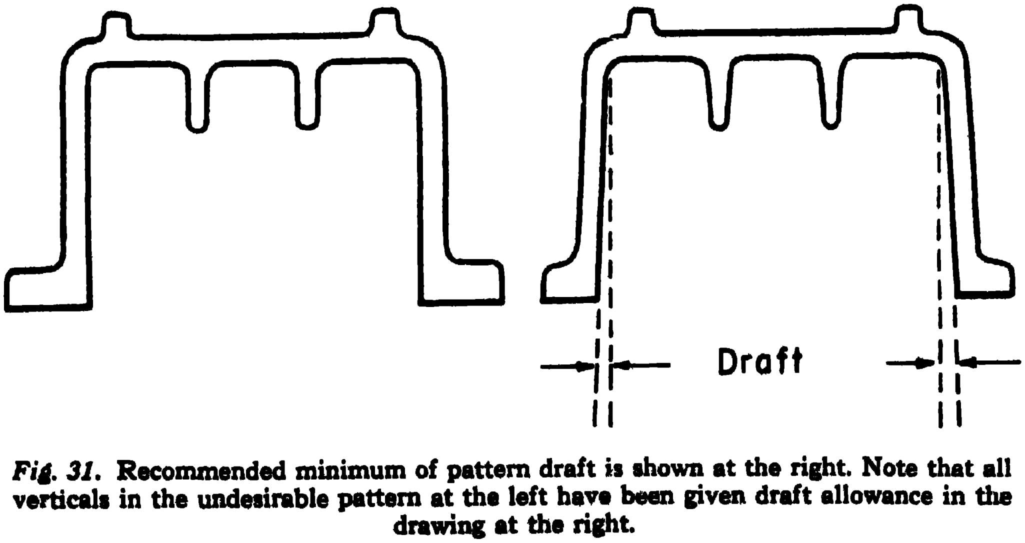


Fig. 31. **Recommended minimum of pattern draft is shown at the right. Note that all verticals in the undesirable pattern at the left have been given draft allowance in the drawing at the right.**

2. Use Cores Judiciously

Cores, separable parts of a mold, are used to form openings or cavities of desired shape in the casting which could not be produced by the pattern alone. They contribute one of the great advantages of castings—the ability to produce internal hollow sections in the first instance. The designer has, however, to bear in mind that cores add to cost, and their use should be reduced to functional purposes. An application of fundamentals, while the casting is in early design stages, can often reduce the use of cores to the economical minimum. Cores used to cut down the mass of a section are justified and often necessary. In considering designs involving cores other than these, however, the designer should visualize how the foundry will make the part. He may then find that a slight change in design will eliminate cores. A simple pan-shaped casting having an internal flange, as shown in Fig. 32 calls for the use of a core with consequent increase in cost. Redesigned as in Fig. 33 the casting has the flange on the outside and can therefore be made entirely in green sand.

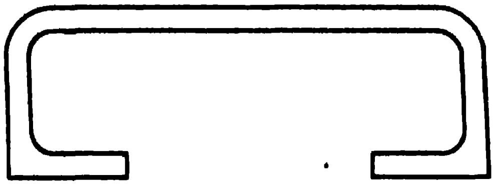


***Fig. 32.* Casting with internal flange requiring the use of a core.**

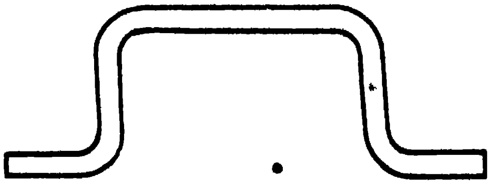


***Fig. 33.* Casting redesigned, the flange being moved to the outside to eliminate the core.**

The raised pads or bosses required for lubrication holes in many castings offer an opportunity to eliminate cores. If the bosses will interfere with the drawing of the pattern from the sand, metal should be added underneath them to remove this objection. Figures 34 and 35 illustrate this fact, and show as well how the appearance of a casting is improved by the elimination of cores. The original design (Fig. 34), required two side cores, one at each side of the center cylindrical section. Because of the design, these cores leave sharp corners where the cylindrical section joins the mounting ears of the casting. Corners such as these are weak and especially liable to cracking or tearing under shock or impact loads. As redesigned (Fig.35) the casting is made without the side cores, providing metal walls tangent to the cylindrical section which join it to the ears by which it is to be mounted and also permit addition of metal between the lubrication boss and the plate section.

Naturally, when a core is used, the design must provide proper anchorage, for the core cannot be permitted to move in any direction. Figure 36 shows the use of slots or windows to locate, support, and anchor the core. When it is not possible to provide two-point bearing for a core,

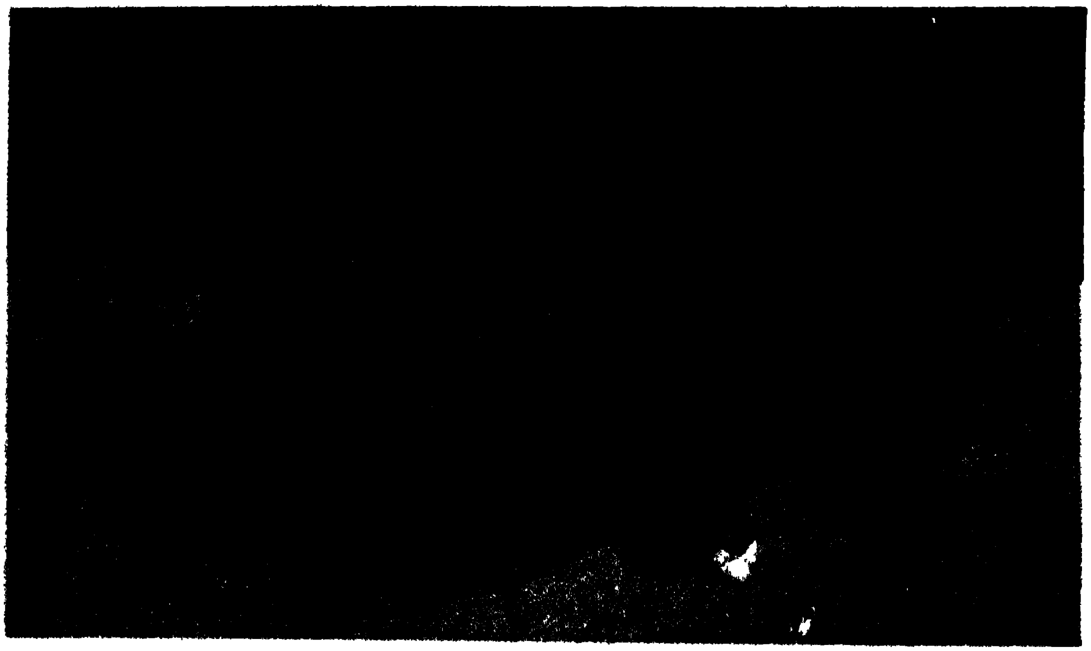


Fig. 34. Gun cradle casting as originally designed, requiring two side cores, which frequently caused mismatch.

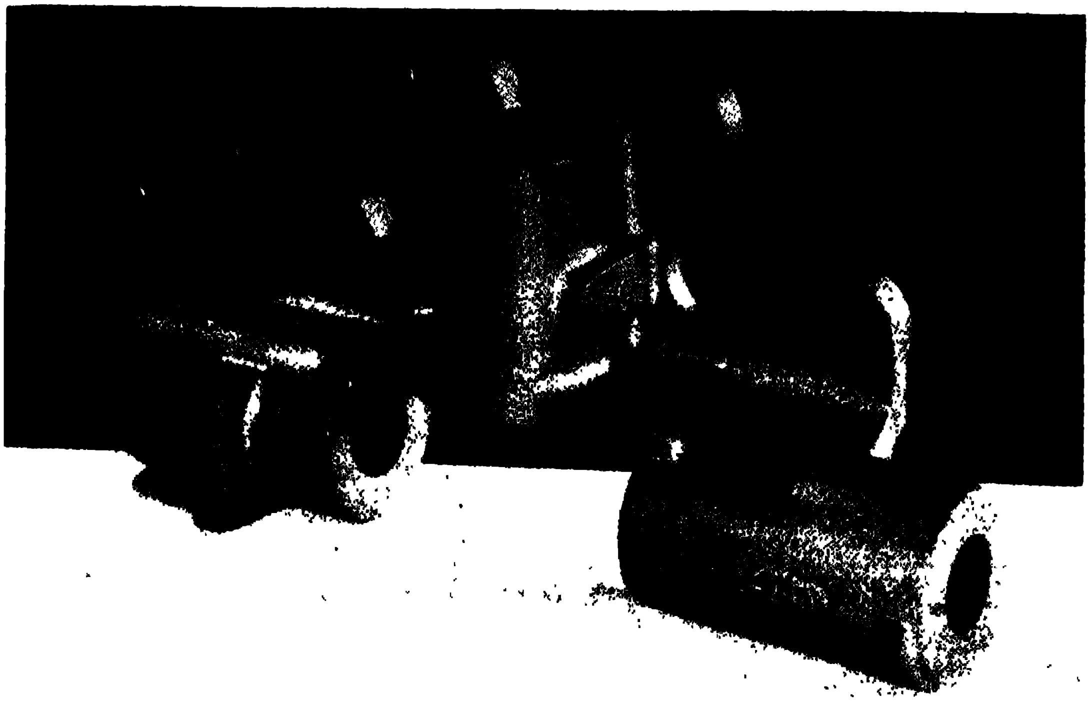


Fig. 35. Gun cradle casting redesigned to eliminate cores and mismatch.

the one core print should be of sufficient size to balance the core and maintain its position while the mold is being closed and poured. When some supplemental support is required, chaplets may be resorted to.

Frequently, cores must be used in the design of a casting, because the piece cannot be so shaped as to avoid them. The designer then should make one core do just as much work as possible. Wheel hub designs are of this type; since they require a center core, they should be so designed

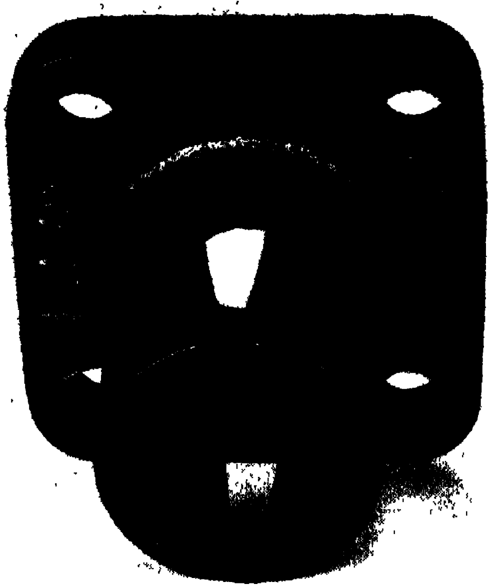


Fig. 36. Use of slots to provide anchorage for cores.

that the center core alone is enough. Figures 37 and 38 illustrate the point. In Fig. 37, both an inside and an outside core are required. The redesign in Fig. 38 requires only the inside core. Another advantage of the redesign is that it brings the plate on the outside. The ribs cast inside are therefore in compression and provide stiffness and strength to withstand the severe shock loads to which a wheel hub is subject. In the redesign, the center core has been made to do its full job, including both the bearing seats and the strengthening ribs.

For the many cases when the designer must make a choice between coring a hole or casting the piece solid, several factors can aid his decision, but they should be regarded as designing guides only, for they will not apply in exceptional cases. They may be summarized as follows:

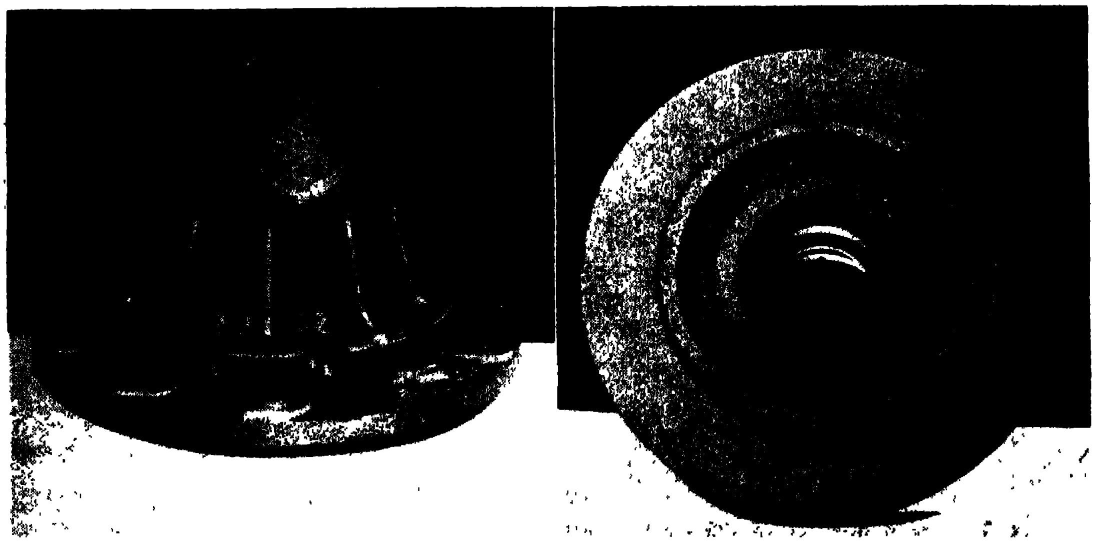


Fig. 37. Wheel hub casting as originally designed.

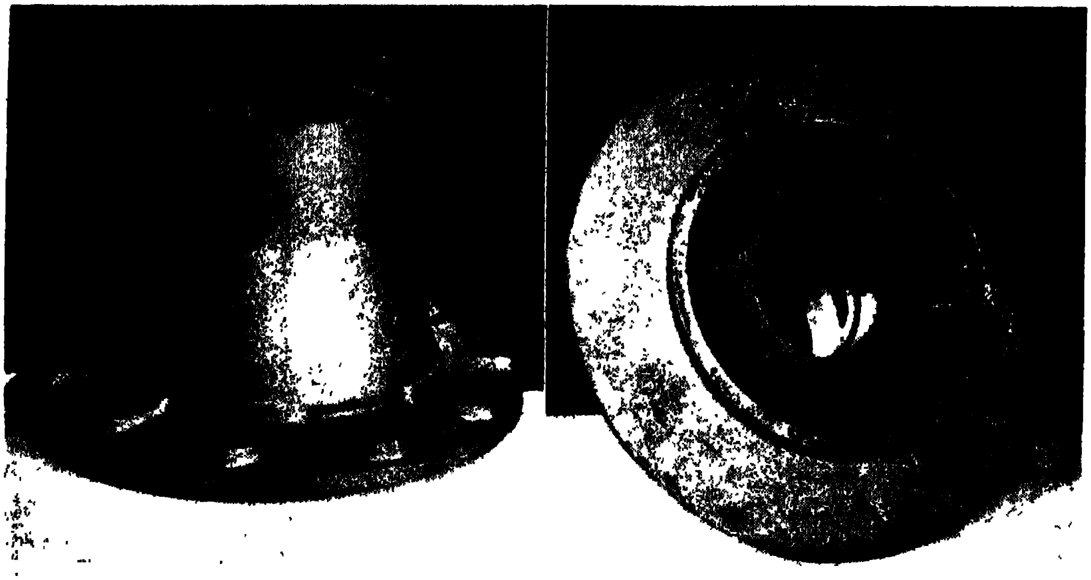


Fig. 38. Wheel hub casting as redesigned.

THE HOLE SHOULD BE CAST IN THE PIECE:

1. When the hole can be cast with sufficient accuracy, and machining can be eliminated or reduced, or when machining time will be saved. If accuracy permits, it is usually quicker and consequently cheaper to machine a cored hole, because less material is to be removed. Since a drill will follow a cored hole, when subsequent machining operations are to be located from a finished hole, accuracy in machining it should be secured through proper piloting of the drill with a jig, or through boring.
2. When it would not be possible to machine the hole because of its location or shape, and the accuracy of the cored hole satisfies the requirement of the design.
3. When the section will be made more uniform and at the same time be as strong and of less weight.
4. When a massive section is so located that it cannot be fed and it is surrounded by a thin section.

THE HOLE SHOULD NOT BE CAST IN THE PIECE:

1. When it will interfere with machining operations.
2. When several holes are required which must be in accurate relation to each other or which can be gang-drilled, punched, or put in the piece more accurately or more economically from the solid.
3. When the hole is too small for foundry production.
4. When the hole is of such a size or in such a location that cleaning it is impracticable.

If the diameter of the hole is equal to or greater than its depth, and if sufficient draft is permitted, the hole can be made in green sand. Otherwise a dry-sand core should be used.

Holes can be made in malleable iron castings by punching or drilling, as well as by coring. When feasible, however, the ability to punch holes is a very valuable feature of malleable iron, since the punching operation is much faster than drilling. Punching is recommended when the thickness of the metal to be punched is less than the diameter of the hole, if it will be an economy as compared to coring. Since malleable iron is ductile, holes may be sized by a drift forced through a cored hole. The drift which expands the hole slightly and leaves the surface fairly smooth, is usually about .005-inch greater in diameter than the cored hole.

In the design of an ear or lug for bolting or riveting a malleable iron casting to another part, recommended policy is to have the radius of the ear at least equal to the diameter of the bolt-hole. For example, if a 9/16-inch hole is required, for a one-half-inch bolt, the radius of the outside of the lug should be at least 9/16-inch. A radius of five-eighths or even 11/16-inch would be preferable. In accordance with one manufacturer's experience the following practice is recommended regarding stock around rivet holes:

W	X	Y	Z
⅜	¼	9/16	⅜
⅜	⅜	½	5/16
⅜	½	½	5/16

W = diameter of rivet hole
X = metal thickness
Y = fillet radius
Z = edge distance

All dimensions in inches.

3. Carefully Consider Size Tolerances and Finish Allowances

The white iron from which malleable iron castings are made contracts about one-quarter inch per foot during solidification and cooling to room temperature, as is explained in Chapter IV. This original shrinkage is followed, in malleable iron manufacture, by an expansion of approximately one-eighth inch per foot during heat-treatment. The malleable iron industry hence generally uses an average shrinkage allowance of one-eighth inch per foot, which is slightly varied in some cases, the variation being imperceptible in small castings. Thus, to allow for shrinkage, the patternmaker may use a "shrink rule," which is 12⅛ inches in length, divided into 12 equal parts, each of which is equivalent to one inch in dimensions of the casting after cooling. Conversely, for checking measurements of white iron castings, to allow for the expansion of approximately one-eighth inch per foot that will occur in heat-treatment, an "expansion rule" is used. This is 11⅞ inches per foot in length, divided into 12 equal parts, each equivalent to one inch in dimensions of the casting after malleablization.

Depending upon the design of the casting and the use for which it is intended, size tolerance may be critical in some dimensions and unimportant in others. Depending upon the design of the casting and the method of locating the pattern in the mold, relatively close size tolerances may be rather easily held in certain dimensions and only with great difficulty in others. Dimensions in the cope or drag section of a mold can be held more accurately than those measured across the parting surface. Dimensions at gate or feeder locations may be subject to more variation than those elsewhere in the casting. Somewhat greater control of dimensions can be attained in castings produced from a machined pattern than in castings produced from one that is cast. Where close tolerances are needed it is advisable to use a mounted pattern rather than a cast plate pattern. An advantage of the mounted pattern is that in repetitive production it facilitates dimensional refinement.

Castings of complex design and those having flanges or projections are likely to require special treatment as far as shrinkage allowance is concerned. These factors and others such as the size of the castings, the relative masses of core and metal involved, varying section thickness, pouring temperature, and mold material should be borne in mind when user and producer seek agreement on allowable size tolerances. The objective of such agreement is to assure both economical casting production and fulfillment of the requirements of the finished part. Approximate values which may be held in malleable iron castings under favorable conditions of design and equipment are given in Table 1.

TABLE 1. DIMENSIONAL TOLERANCES FOR MALLEABLE IRON CASTINGS, GREEN-SAND MOLDING

Outside Dimensions	*Dimensional Tolerance*
Up to 4 inches	± 1/32 inch
4 to 8 inches	± 3/64 inch
8 to 12 inches	± 1/16 inch
12 to 24 inches	± 1/8 inch

For shell molding and sodium silicate–carbon dioxide molding, which are discussed in Chapter IX, size tolerances are, in general, from one-third to two-thirds of those for green-sand molding, depending upon the size of the casting and the length of the dimension on which the tolerance is calculated.

Since shrinkage allowance and the size of gates and feeders necessary to produce sound castings vary with different metals, it is most important that the foundry be consulted when patterns constructed for the requirements of another metal are to be adapted for the production of malleable iron castings. Minor modification often is found to be sufficient for the conversion from other metals to malleable.

Some of the foundry factors involved in holding dimensions may be considered to advantage in greater detail. First, the designer must realize the possibility of some misalignment between the top and the bottom half of a mold. Though many precautions are taken to minimize this condition, it cannot be entirely avoided. Hence, if the relationship of certain casting surfaces is particularly important, the designer should try to plan the casting so that the foundry can make all these critical surfaces in the same part of the mold. Their relation to each other will then be more accurate. Surfaces approximately parallel to the parting plane will be the most accurate. Not only is it preferable to have critical surfaces in the same part of the mold; it is also important that the casting be chucked, in machining, on one of these surfaces. Redesign for simplification, as in Fig. 39, is frequently well justified.

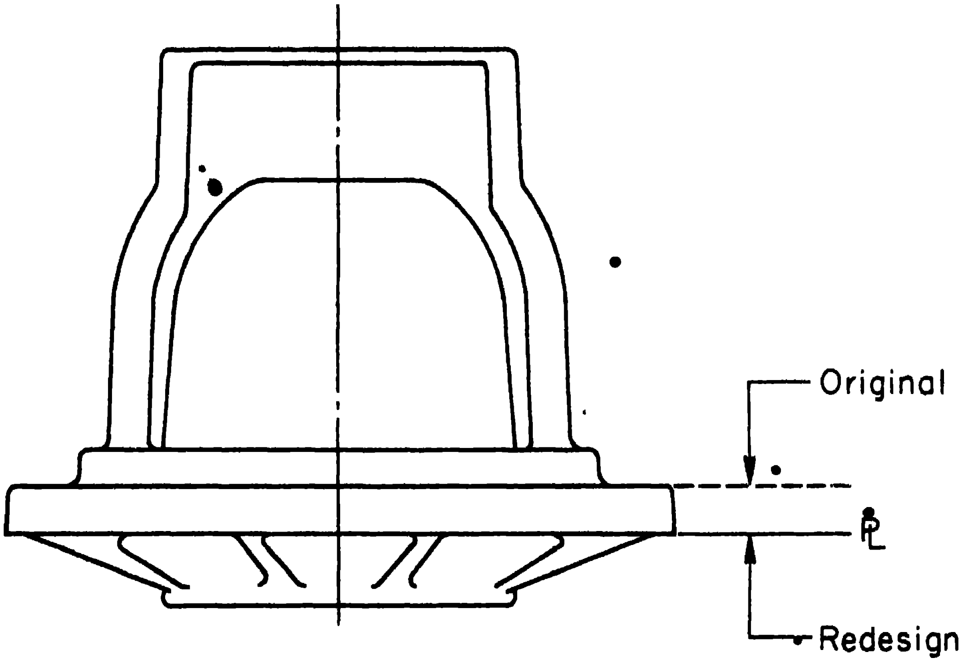


Fig. 39. **This picture shows an example of a differential case in which the parting line was changed from the upper edge of the flange to the lower edge to place the flange and the major portion of the body in the same mold half.**

When a core is used, a similar condition arises, since the location of the core in the mold is subject to some variation. A core print must be slightly larger than the core used with it, for otherwise the core would not fit into the core print impression. Though with accurate pattern equipment and sound foundry practice the variation will be small, the relationship between the two surfaces will not be as accurate as that between two made in green sand. Likewise, the use of cores may leave a mark or fin on the casting at the junction line where the cored surface blends into the molded sand surface. Machining or finishing operations obviously should never be located from these spots.

When great accuracy is necessary and the quantity involved warrants the making of straightening dies, malleable castings are die-straightened in presses. This reduces the required finish to a minimum and assures uniformity for locating machining operations. Certain castings lend themselves very satisfactorily to coining operations and holding of very close tolerances. Small nuts, one-half in. in thickness, have been held as close as .007-inch on thickness and .003 to .005-inch on flatness, eliminating facing operations. Of course, as a casting gets larger, this accuracy in turn decreases, Even large brake shoes, for example, 15 inches in diameter and 7 inches in width, are being made very satisfactorily holding tolerances of less than .020-inch on a curvature. In this case, the customer eliminates all the machining on the liner face and actually only has a finish grind operation in which he removes about .010-inch from the highest parts on the casting.

The type of finishing operation to be used on a casting determines the finish allowance which must be incorporated into the design. Experience is valuable in establishing finish allowances which are correct in that they assure that the castings will be cleaned up during machining. Since malleable iron machines more easily than other ferrous metals, it is generally advisable for the designer to be generous with the finish allowances he makes. The following are recommended for malleable castings:

For milling:	1/16-3/32-inch for small castings 1/8-3/16-inch for medium castings and more for larger castings
For reaming:	3/32-inch on the diameter for cored holes under 1-inch 1/8-3/16-inch on the diameter tor medium holes and more for larger holes

For castings which are press-straightened, allowances may be less than those listed. In turning or boring diameters larger than five inches, it is well to allow one-quarter to three-eighths inch on the diameter. If locating points are a considerable distance from the machined surface, additional allowance should be made.

How the castings are to be located in machining operations is of importance when the casting is being designed and the amount of finish allowance is being established. The foundry should be given this information. Location points should never be established at a place where a gate or feeding head has been removed, and should not be at the parting line or on a cored surface. The producing foundry should be given the proposed machining set-up so that it can recommend the most practical amount of finish on all machined surfaces. By all means, the drawings should show what surfaces will be machined, for this fact will govern the layout of the pattern equipment.

DESIGN PROBLEMS RESOLVED

Thus far in this chapter we have considered two basic groups of principles which must be taken into account in the design of malleable iron castings and the preparation of patterns embodying those designs in the most efficient fashion for dependable and economical production.

The necessity for understanding and cooperation between the customer's design engineer and the foundry engineer has been stressed in that discussion. There now follows a section describing in practical terms significant design problems, in which this kind of collaboration has resulted in effective and satisfying solutions.

Relieving the surface area for more effective coining is one of the means to economical production. This has been utilized in the valve box cover shown in Fig. 40. Here metal has been removed to facilitate flow in coining the thickness to ± .010-inch.

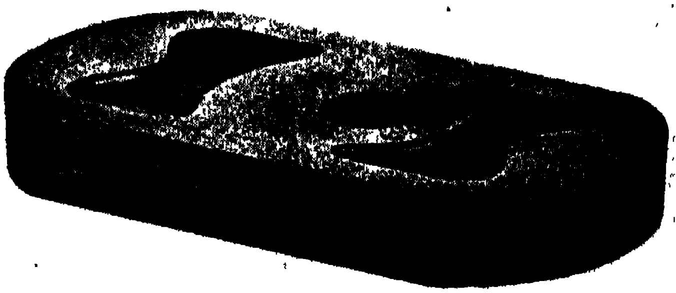


***Fig. 40.* Metal has been removed from the surface of this valve box cover to facilitate coining.**

Another way of securing economy in production is illustrated in Fig. 41. In the small crank shaft shown, tie-bars have been added to prevent distortion during heat-treatment. The metal between the throws not only serves as a tie-bar but also provides an effective gate location. When it is machined out, the gate is removed as well.

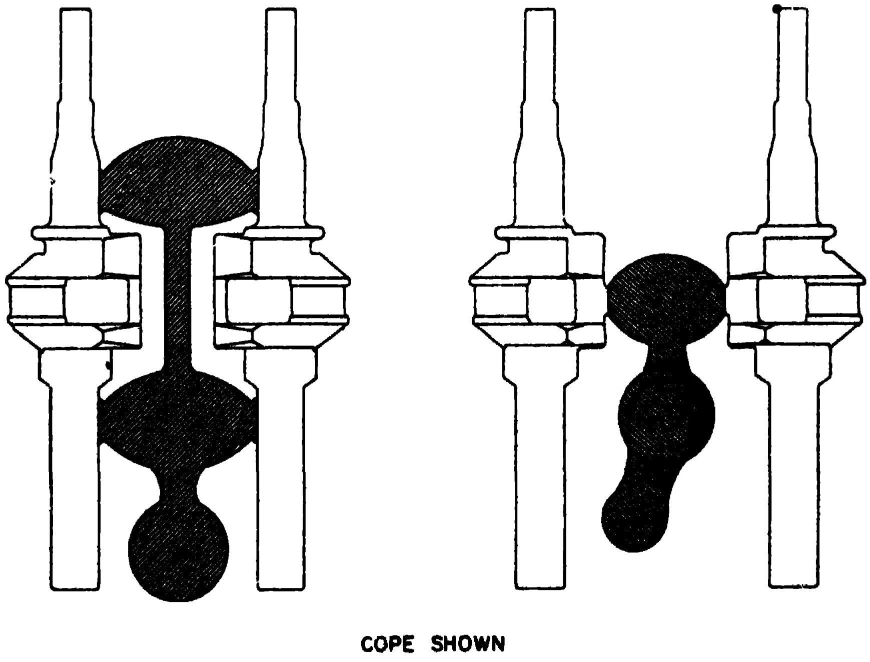


***Fig. 41.* On the left, the original gating of the crankshaft with the feeders on the shaft. On the right, the redesigned gating system with the feeders connecting the two throws and acting as a tie bar.**

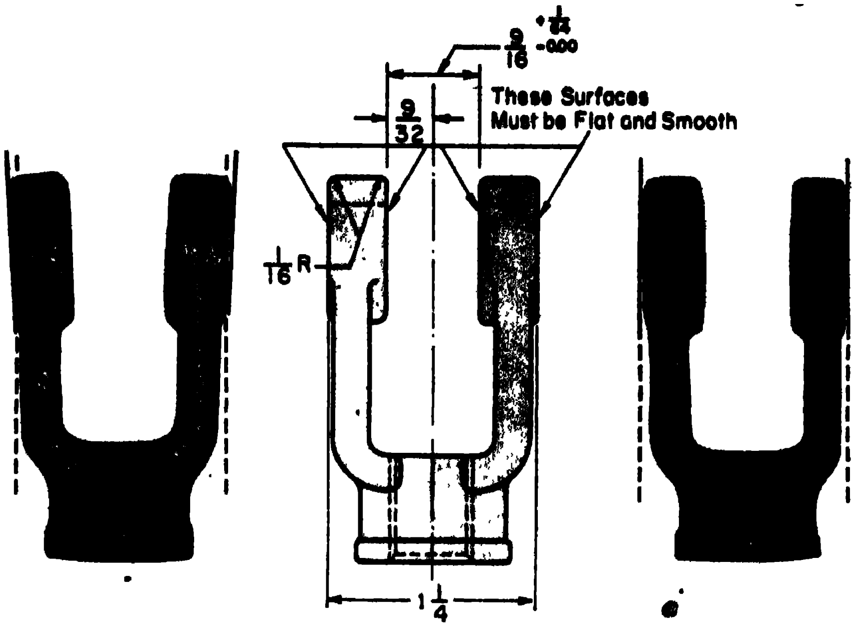


Fig. 42. This pearlitic malleable yoke was coined to close tolerances. The drawing indicates the desired dimensions. The finished casting, which has been coined to the dimensions shown, is at the right.

In Fig. 42, the use of die pressing—a procedure fostered by the ductile characteristics of malleable iron—is presented. The blueprint for this pearlitic malleable iron yoke specifies the indicated surfaces to be "coined parallel to plus .016, minus .000 inches."

The 12″ inside diameter bead ring, shown in Fig. 43, is coined to specified tolerances of ± 0.010″ on the inside diameter and ± 0.0075″ from the mounting face to the underside around its entire length.

An application of die pressing to attain minimum machining stock is illustrated in Fig. 44. Here coining eliminates a milling operation. Coining the radius of this brake shoe makes possible a single light disc grinding to remove high spots before the lining is mounted.

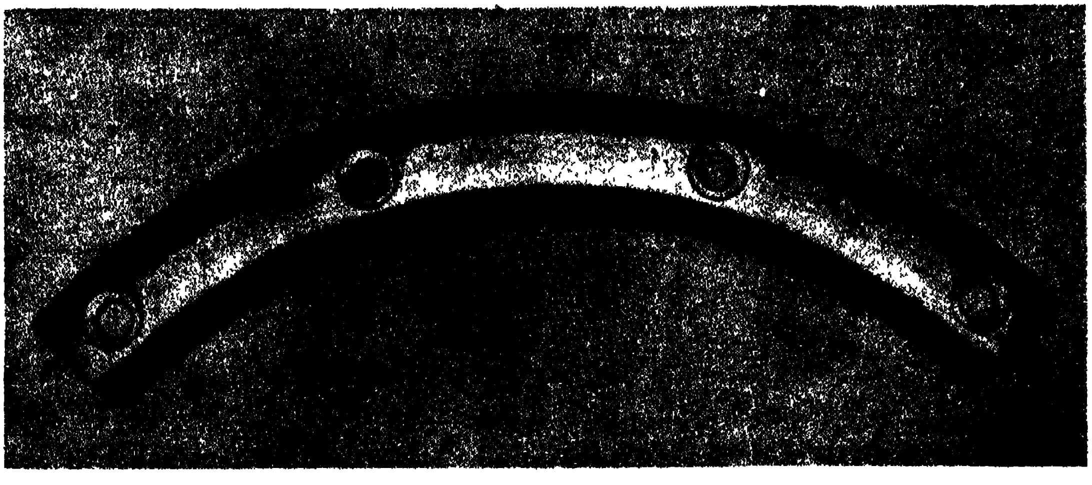


Fig. 43. The malleable iron casting shown here is a section from a bead ring. The inside radius is precision coined to ± 0.010″, thus eliminating all machining.

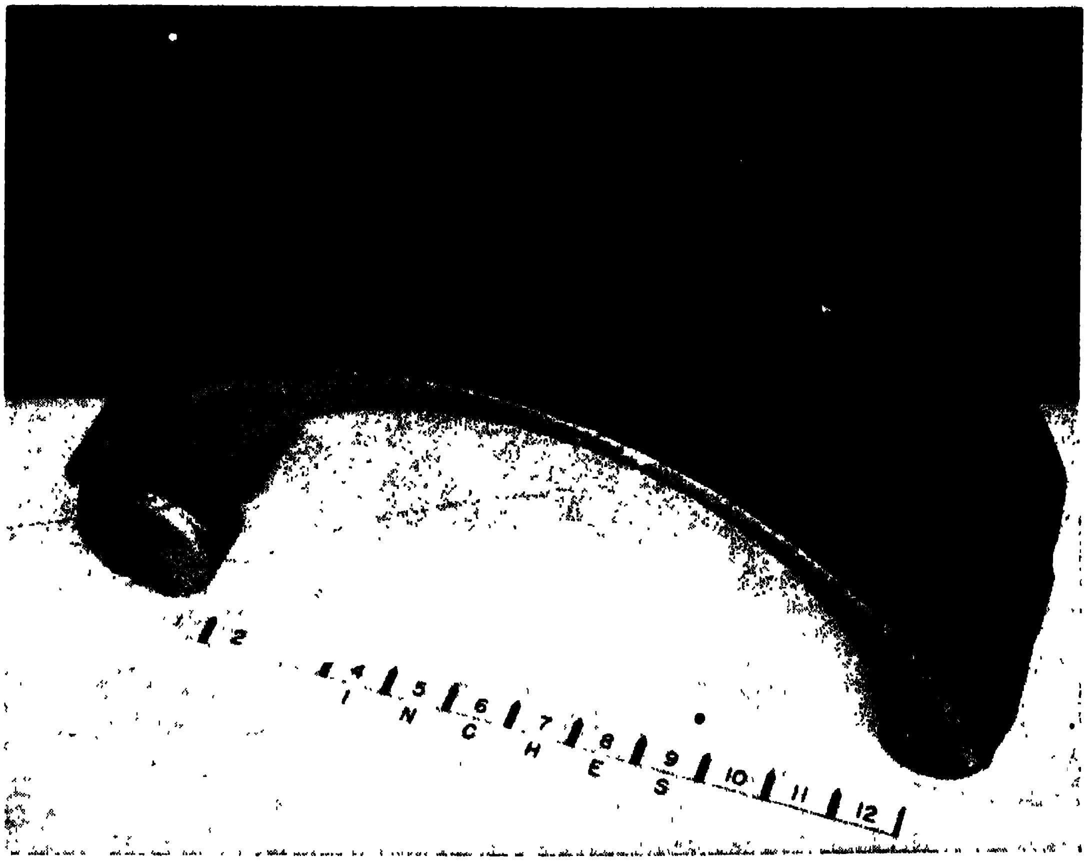


Fig. 44. **This brake shoe was coined and a milling operation was eliminated.**

Malleable iron, because of its ductility, can readily be punched, and punching can at times be used to eliminate a drilling operation, as is shown in Fig. 45. In the casting illustrated, three holes were punched, eliminating other machining operations. Punching permits boring without drilling, saving both time and money in many instances.

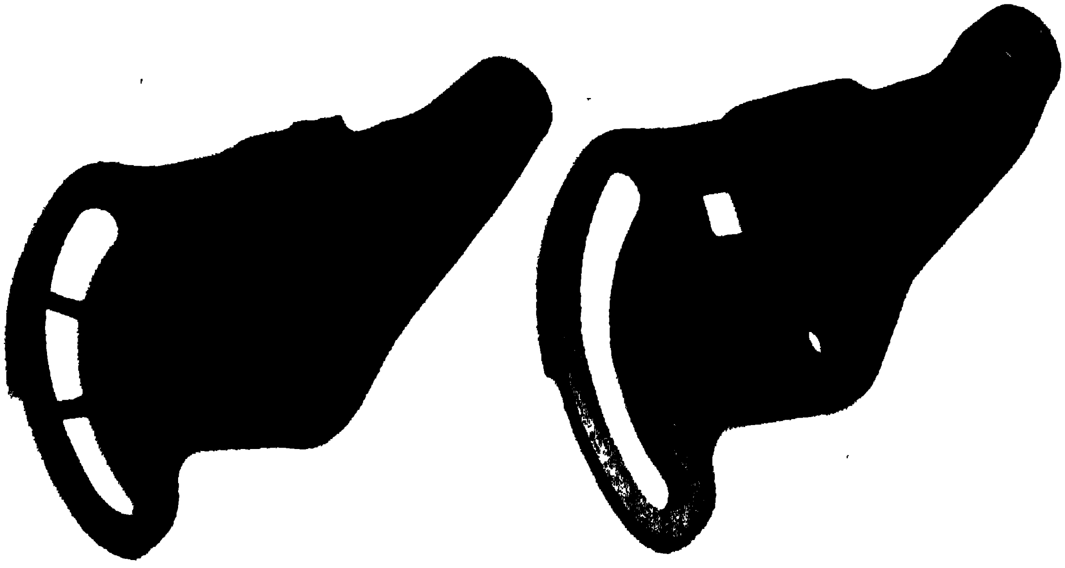


Fig. 45. **The rough (left) and finished (right) malleable iron idler arm casting illustrates punching and coining to eliminate machining and to reduce cost.**

Fig. 46. **The picture on the left shows the railway door latch as cast. By using a flat cast design and then cold bending, coring is unnecessary.**

The two castings shown in Fig. 46 offer another example of the employment of the ductility of malleable iron for economy in production. The railway door latch is cast flat, making coring unnecessary. Subsequently, the latch is readily brought to the final form required by the design by a bending operation.

The excellent hardenability of pearlitic malleable iron is used to advantage in the rocker arm shown in Fig. 47. The indicated wear surface is selectively hardened.

When designing a casting to fit into a tube or pipe, three or four narrow flutes can be arranged on the surface of the casting, as shown in Fig. 48. The flutes are the fitting points, eliminating machining to secure

Fig. 47. **The pad of this pearlitic malleable iron rocker arm has been selectively hardened to provide additional wear resistance.**

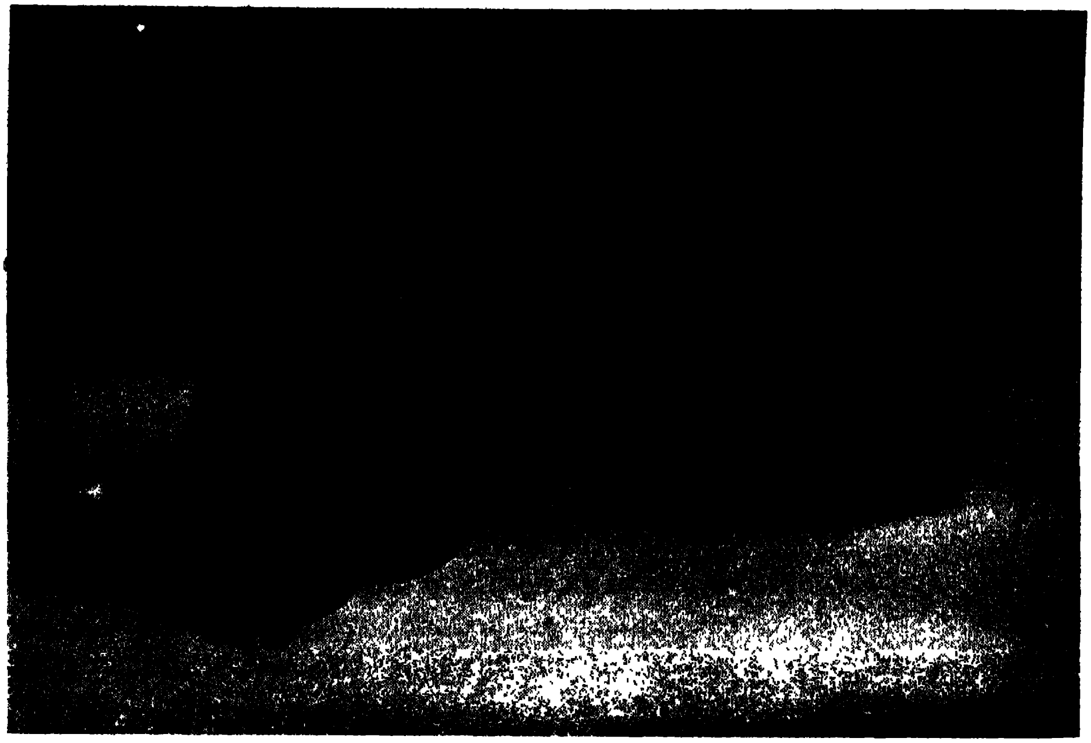


Fig. 48

the desired fit. Good pattern equipment should be used, and the required size and fit should be worked out with the foundry.

The casting of drill-spotting holes, as in Fig. 49, provides a starting point for drilling; and where the hole does not require an exact location, it is a practical way to eliminate a drill jig.

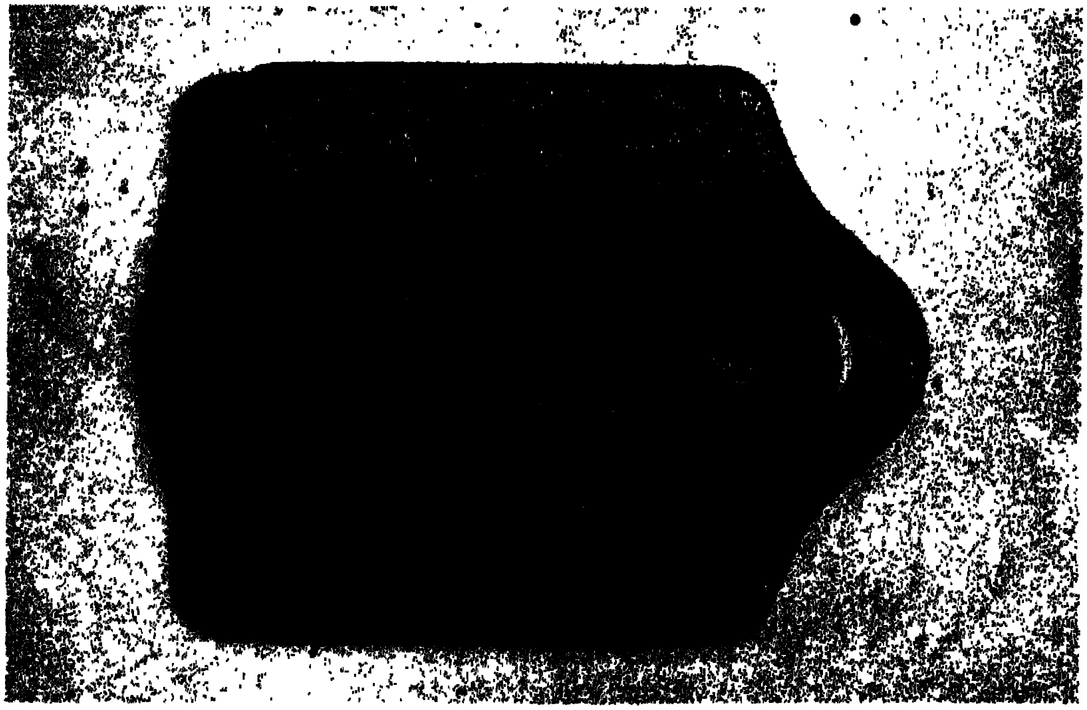


Fig. 49

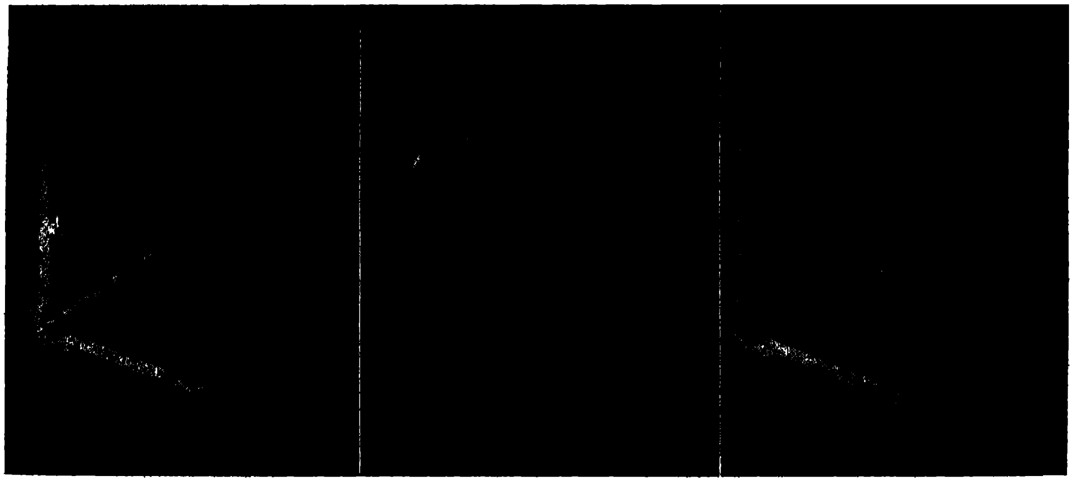


Fig. 50

Fig. 50 shows three ways of designing a casting with mounting surfaces at 90 degrees to each other, yet without undesirable sharp inside corner that might be expected. If the corner is "relieved" in one of these ways, the danger of a crack or tear is removed. At the left, Fig. 50 shows a type of relieved corner sometimes used. That at the right is in more general use because it permits green sand molding. In the center the use of raised mounting bosses is illustrated. This kind of design is suitable when the amount of surface contact required is not large. In this type of construction, it is usually desirable to add metal back of the bosses on one surface of the casting in order to avoid the need of cores.

By using stress-analysis, a malleable hinge Fig. 51 (right, bottom)

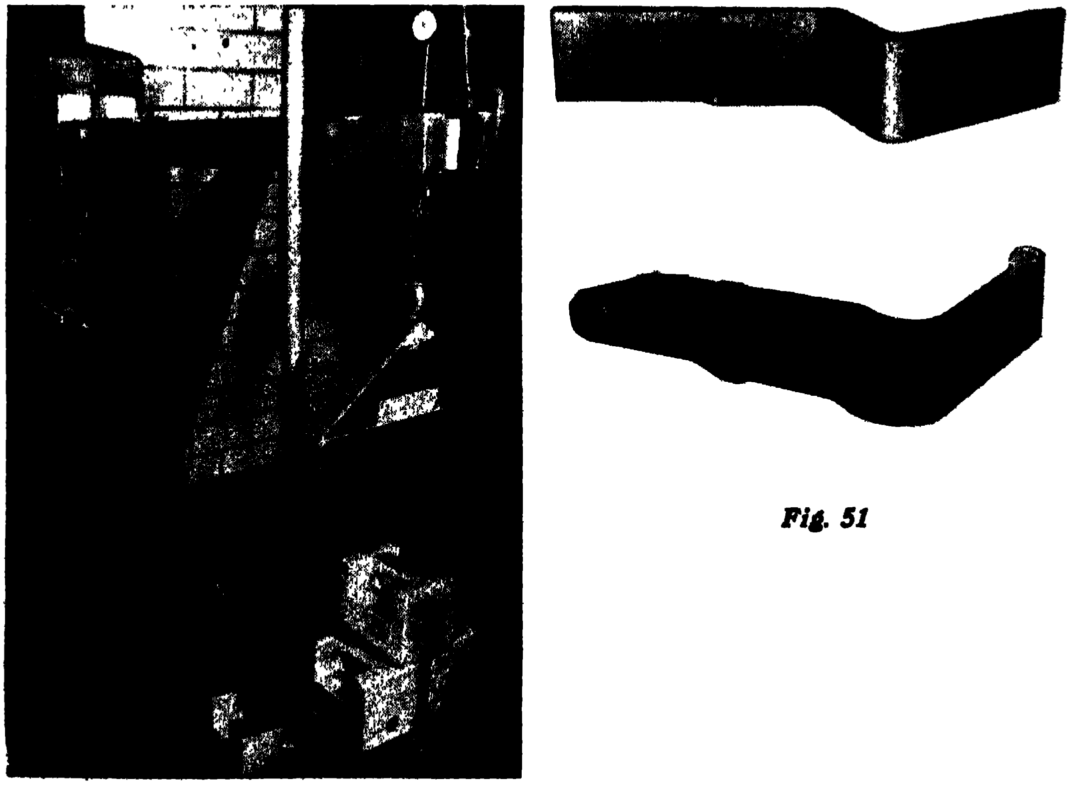


Fig. 51

could be designed which combined greater strength with a reduced weight at a lower cost when compared to the stamping (right, top) which it replaced. The automotive door hinge shown in Fig. 51 illustrates this point. At the left in Fig. 51 can be seen some of the test apparatus used in the stress-analysis development in the hinge.

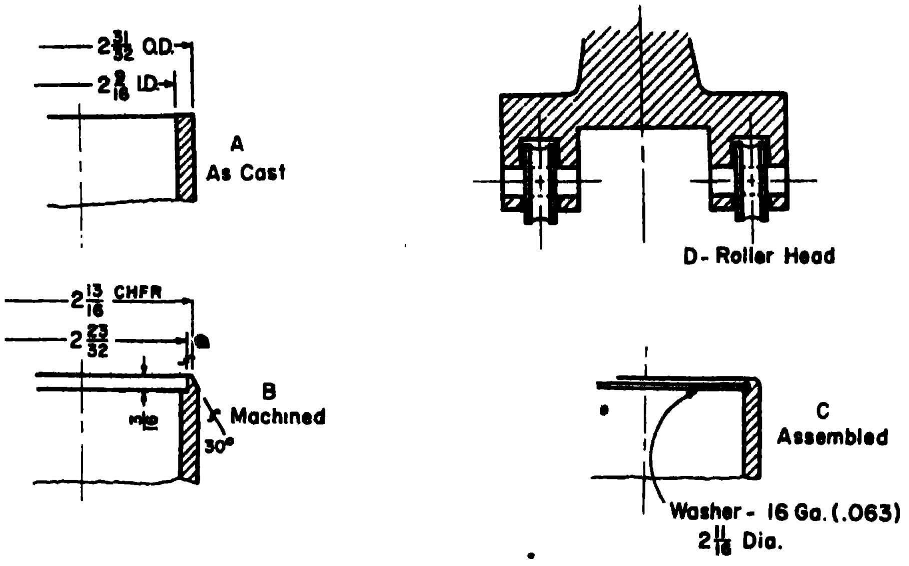


Fig. 52

The sketches in Fig. 52 present another utilization of the ductility of malleable iron, this time in a rolling or spinning operation used in the manufacture of jacks. The jack body is cast cylindrical as shown at A, and then is counterbored and chamfered on the outside as shown at B. A washer is inserted in the counter bore, and to lock it in place, as at C, the malleable iron is rolled over by a roller head D.

The two-piece assembly shown in Fig. 53 is a snap coupler for a fertilizer pump. Conversion to a casting reduced the unit weight from 2.8 pounds to 1.62 pounds. The photograph on the right shows the use of silver brazing in joining the stud end cap to the malleable coupler.

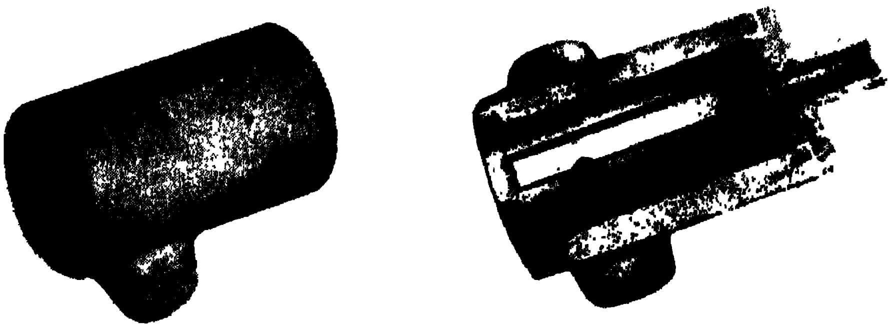


Fig. 53

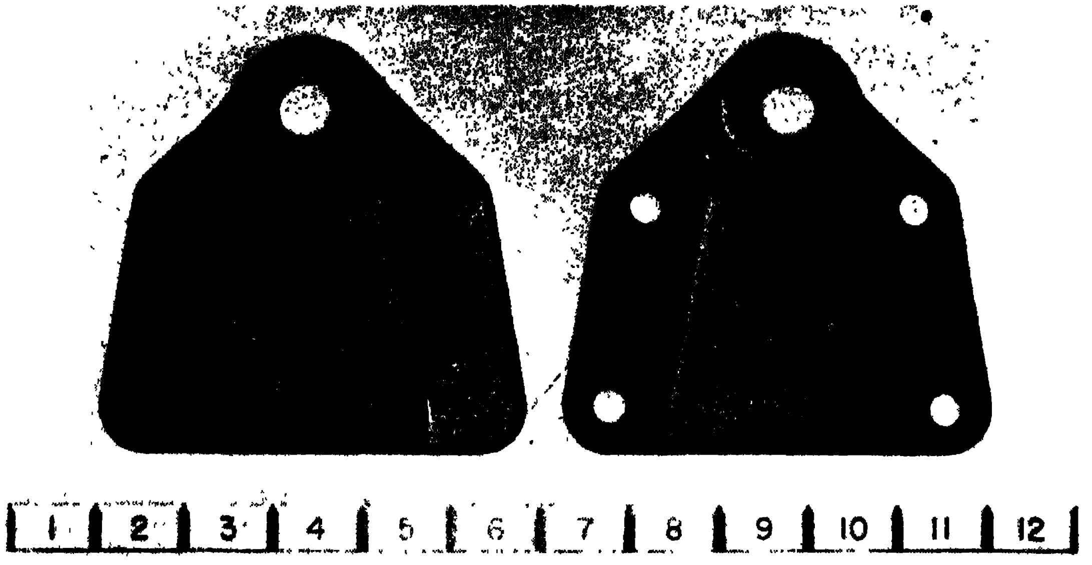


Fig. 54

Under proper conditions, holes in malleable iron castings can be punched instead of drilled, as is illustrated in Fig. 54. The diameter of the hole should exceed its depth, and as in other materials, the holes should not be located too close to the edge of the piece.

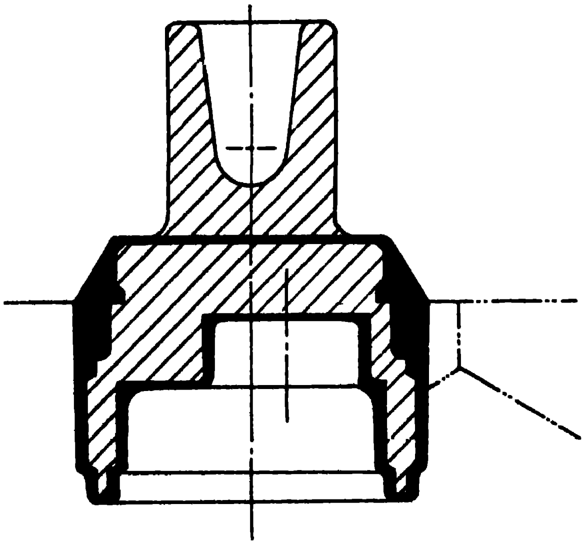


Fig. 55

The piece shown in Fig. 55 is to be machined all over. This drawing shows a booster body casting with a chucking lug cast integrally with the part. After the lug has served its purpose to hold the part during machining it is cut off.

Welding is used in Fig. 56 to fasten a malleable iron casting to a steel rod or tube. The oval-shaped opening in the casting permits a button of weld metal to be deposited on the steel rod, locking the casting in place.

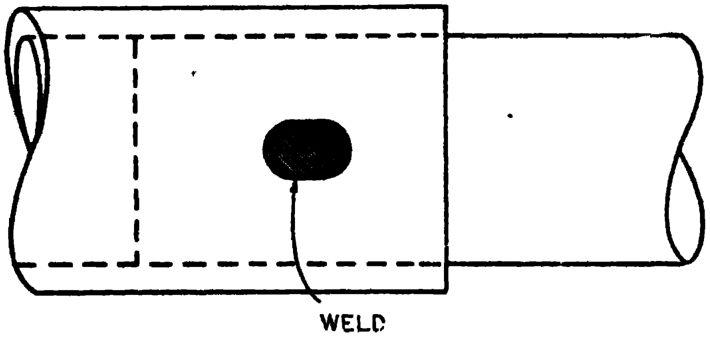


Fig. 56

A punch press is used in the crimping operation shown in Fig. 57 where A is the body of a jack, B the base. Neither part is machined, the two rough castings being assembled as shown at C by means of a crimping head D attached to the rim of the punch press. This way of assembling the units utilizes the characteristic ductility of malleable iron castings. It is an inexpensive and thoroughly satisfactory method.

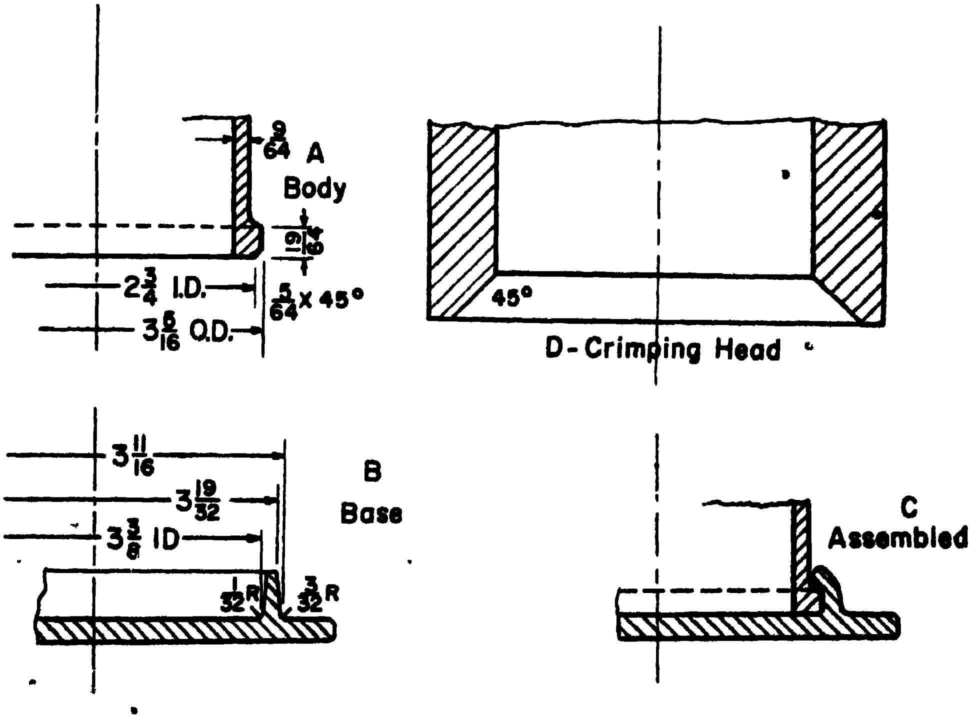


Fig. 57

The two parts shown in Fig. 58 illustrate a conversion from a three-piece assembly to a single malleable iron casting. The part—a mail-box leg—originally comprised a foot casting, a stamping, and a rivet to hold the two together (left). Appearance of the assembly was none too good, nor was its resistance to corrosion satisfactory. Conversion to malleable iron (right), with no increase in weight, resulted in an improved appearance and enhanced corrosion resistance.

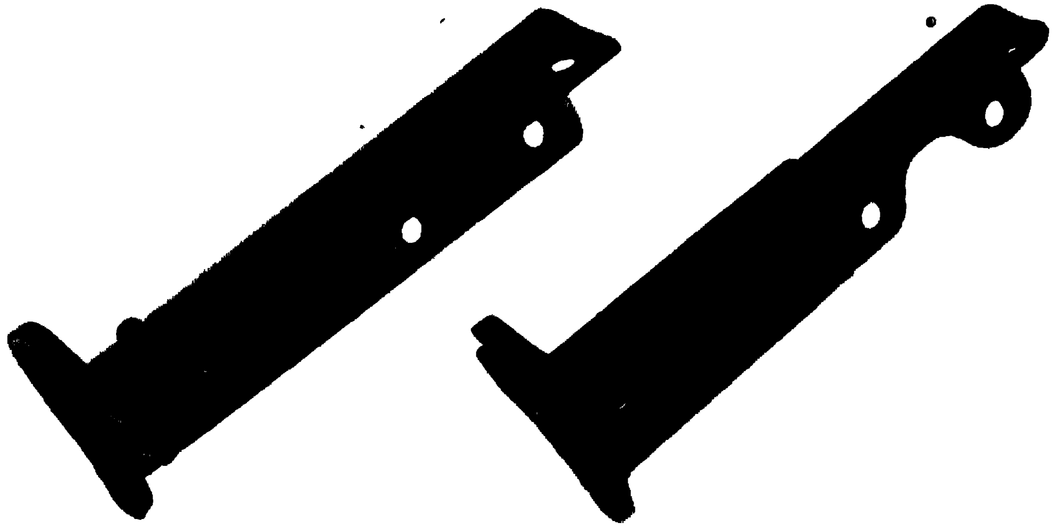


Fig. 58

Redesign to observe the section principles discussed earlier in this chapter and thus to gain toughness and structural strength is illustrated in Fig. 59. The lever as originally designed, extreme left, was deficient in these qualities. As redesigned, center, with an H-section, some redistribution of metal at the base, but no increase in weight, the part attained the needed high degree of toughness and strength. This is illustrated in the example at the right, which has bent but not broken when subjected to many times its functional load.

The lightness that can be secured in malleable iron with no loss in strength is exemplified in Fig. 60. The solid formed insulator bracket shown at the left weighed 4⅜ pounds. The well designed malleable iron

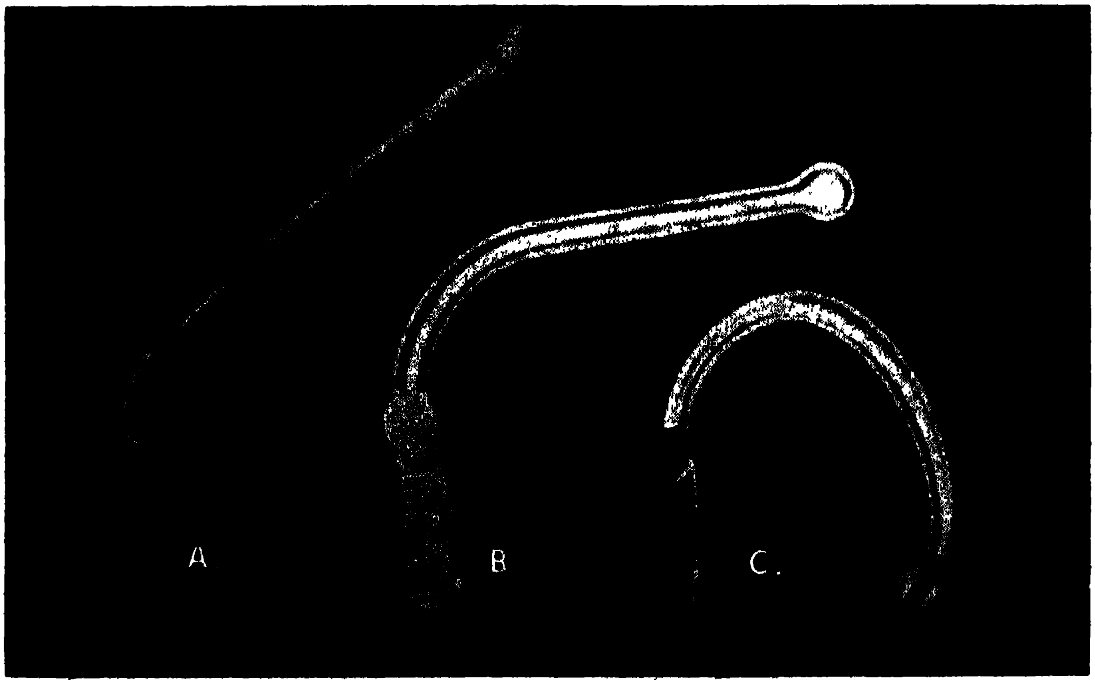


Fig. 59

replacements, 38 per cent lighter in weight (2¾ pounds) is equal in strength, is easier to handle, assemble, and mount, has greater corrosion resistance, and costs less.

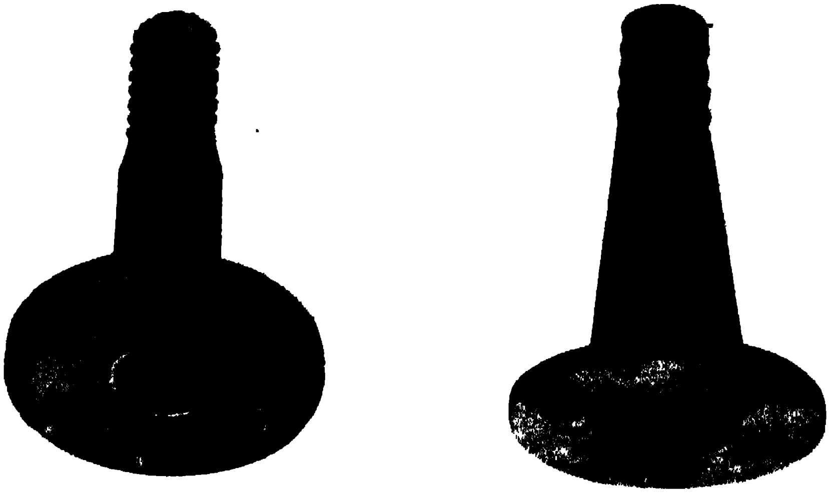


Fig. 60

A good illustration of redesign to eliminate cores and increase production is given in Fig. 61. In the original design, recesses were cored out on the outside of the casting to decrease its weight. Two cores had to be made and be set by the molder for each casting. Placing the lighteners to face each other between the two elements of the casting permits the use of a single core, halving the number of cores to be made and placed.

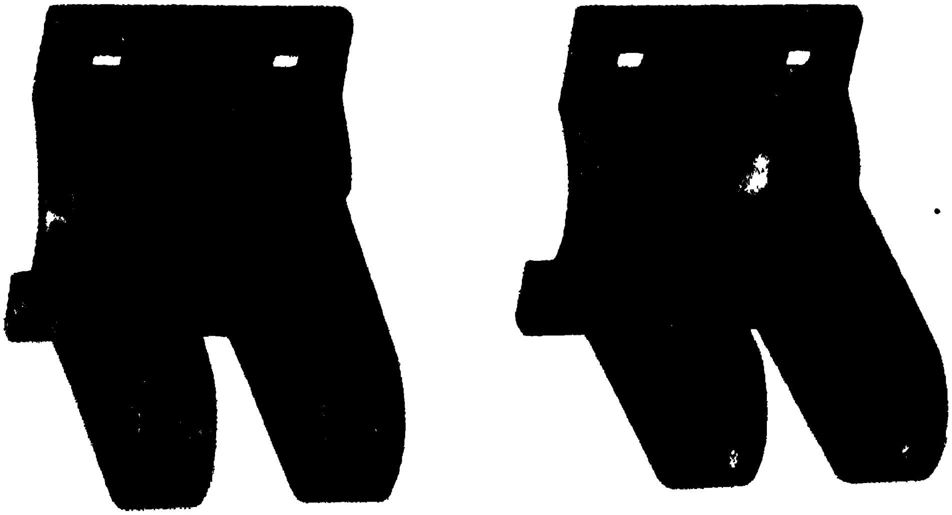


Fig. 61

The refrigerator car brine valve in Fig. 62 was originally a two-part assembly cast in another material. When failures were encountered in the bottom casting, malleable iron was substituted. When further failures occurred in the top casting, decision was made to redesign the entire assembly as a one-piece malleable iron casting. There were no more failures.

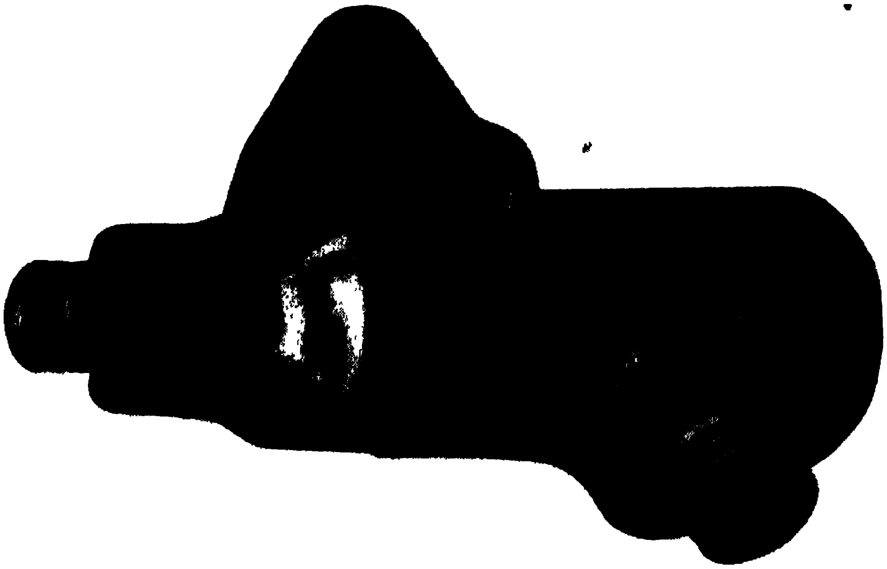


Fig. 62

The 7 ounce malleable casting illustrated at the right (top) in Fig. 63, part of a tube flaring tool, failed frequently in service. After experimental stress analysis with the equipment shown, a modified design was effected. The bottom photograph indicates the same part after redesign in which a more favorable stress pattern was produced. With this design, service failures were eliminated.

A change in pattern equipment worked out by joint action of customer and foundry is shown in Fig. 64. It more than doubled daily production by the molder. The original equipment required the use of the large core shown at the right of the pattern, and produced but one casting per mold. Revision of the pattern cut the size and weight of the cores

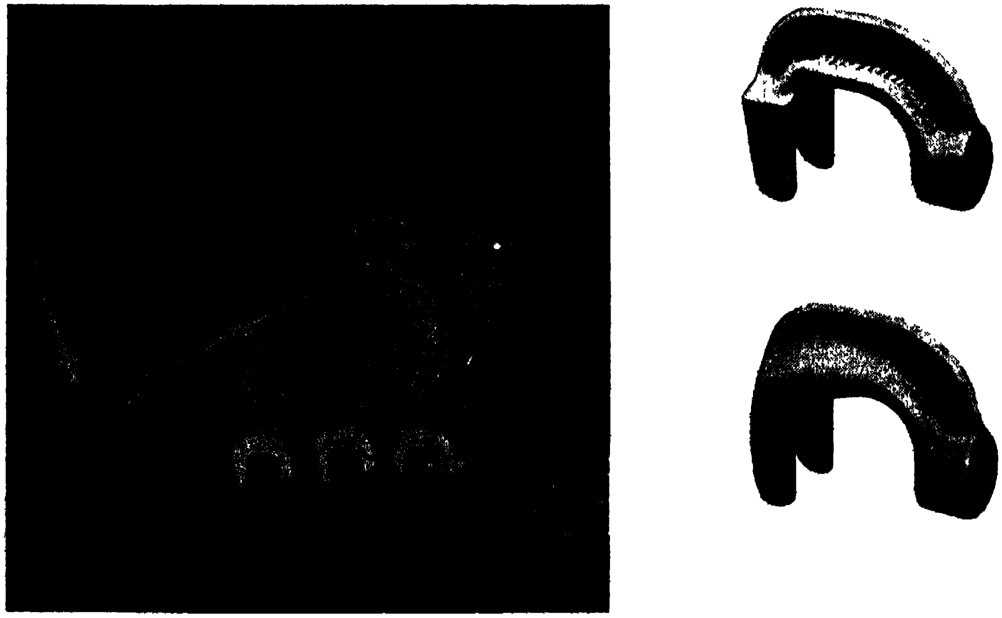


Fig. 63

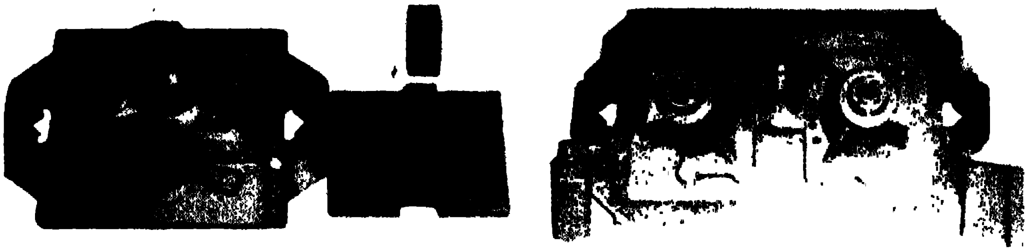


Fig. 64

by 67 per cent, produced two castings per mold, and reduced remelt (gates and feeders) by 43 per cent, thus working to the marked advantage of both customer and producer.

To indicate the versatility of casting design possible in malleable iron, a typical truck differential carrier is shown in the following sequence of illustrations. This particular part, and many others quite similar in design, have been proven by years of satisfactory performance in production quantities running in excess of 1,000,000 castings.

Fig. 65 shows the aluminum working pattern for a heavy duty truck differential carrier. The cope (left) and drag (right) halves of the pattern are mounted on two plates; perfect alignment of the molds made from this pattern is assured by the locating pins and bushings (1). Of particular interest are the cooling fins located at (2) on the cope. These three small fins influence the heat transfer rate of the molten metal in this area of the casting and promote directional solidification. The reader's attention is also directed to the well-designed feeding system. Note the vents which allow easy exit of gases generated within the mold when molten metal enters the casting cavity. The counterbore on the dead feeder head (3) eliminates a green sand core in the top of the feeder, while permitting it to function properly.

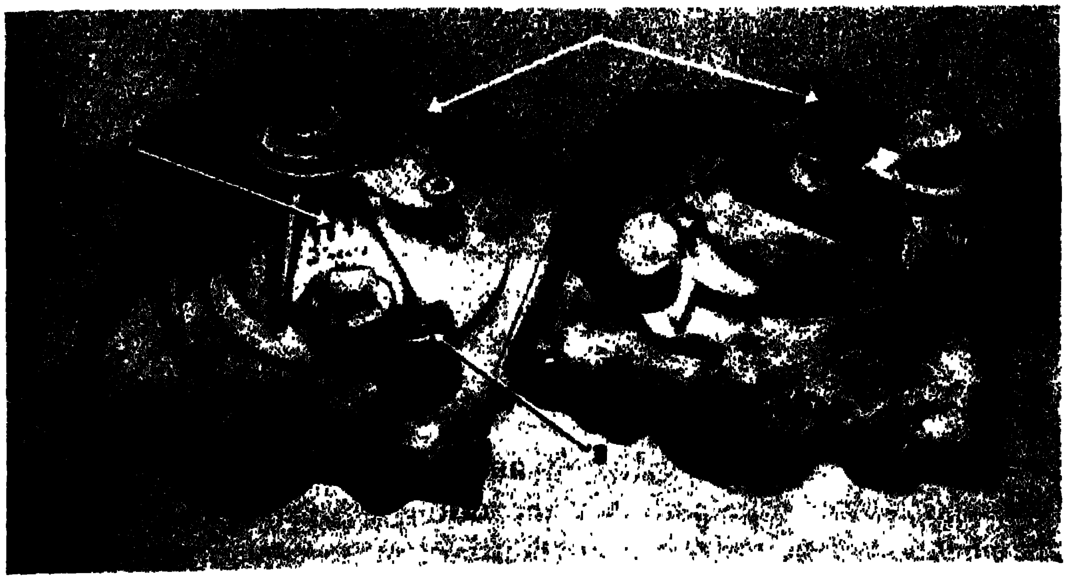


Fig. 65

The assembly of five cores, shown in Fig. 66, is placed on a pallet-type core dryer, baked, and then set in the mold. These cores form the cavities for the oil channels and pinion bearings in the finished castings. The chaplets (4) in the outer assembly serve to support and position the cores. The ceramic-coated white iron chills (5) promote cooling and enhance directional solidification in the central portion of the differential carrier. The coating prevents the molten metal from fusing to the chill and controls the rate of heat transfer.

In the center of Fig. 67 is exhibited a differential carrier ready for machining. The sectioned carrier clearly shows two cored channels which deliver oil to the pinion bearing (6) and the differential carrier case side bearing (7). The central portion of the casting shows another oil channel, the oil supply hole which delivers lubricant to the pinion gear bearing (8). Also visible are the mounting surface for the gear shifter box (9) and

Fig. 66

the mounting pad for the electric or vacuum shifting unit (10). Note that several fundamentals of good design have been applied; sections are well blended, abrupt changes in thickness are avoided, and sharp corners are minimized.

Fig. 67

Figure 68 shows an internal view of the carrier. The three oil holes visible in the center casting are: the differential case side bearing channel (7), the pinion gear bearing channel (8), and the oil distributor (11). A wiper device is fitted into the hole at (11) and serves to remove lubricant from the back of the ring gear and to force it into the various cast channels.

This differential carrier is designed to take the largest gear commensurable with the smallest external dimension to afford maximum road clearance. The finished casting weighs 96 pounds before machining, and

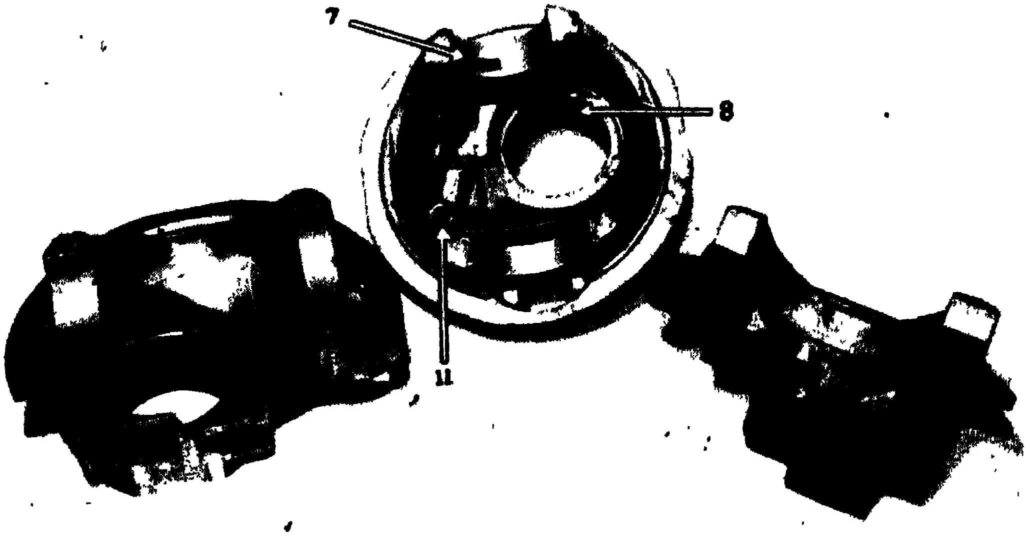


Fig. 68

details of the machining of a carrier of similar design is given in Case *History* 2, Chapter X.

In general, all castings consist of a basic "shape," to which additions in the form of flanges, bosses, ribs, etc. are made. When designing for the casting process, the following points should be taken into account:

1) similarity with already existing parts,
2) the location of the cast component in the assembly for which it is designed,
3) nature of the service conditions, such as environment (corrosive or oxidizing), mechanical properties required (including pressure tightness), type of loading or overloading expected.

Streamlining, i.e. the elimination of sharp corners and the avoidance of abrupt changes in section, is a major objective of scientific casting design. This streamlining has a dual purpose: In the foundry it prevents the formation of hot spots, i.e. areas of restricted heat flow, and in service it will minimize stress concentration.

IX

THE MANUFACTURE OF MALLEABLE IRON CASTINGS

THE MANUFACTURE of malleable iron castings of any of the three classes--standard, pearlitic, and alloy—is fundamentally a two-step process. The first step is the manufacture of white iron castings; the second, their conversion, through controlled heat-treatment, into the desired malleable products. These important engineering materials are made in a hundred or more plants located in the principal industrial areas of the United States. The plants vary in size from those making a hundred tons monthly and designed for the efficient handling of relatively small orders to those producing several thousand tons monthly and mechanized for large-quantity, continuous production. Large or small. however, the malleable iron foundry in its organization reflects the various operations into which the fundamental manufacturing steps are divided, as shown in the accompanying flow chart. (Fig. 1.) This chapter will be similarly organized, discussing in sequence first the operations necessary to the production of white iron castings: melting, molding, core making, pouring and subsequent shaking out, cleaning, and inspection; then the operations performed during and after the conversion of the white iron to malleable iron will be covered: heat-treatment, final cleaning, finishing, and inspection.

MELTING

The first operation, melting, converts the raw materials of the charge into a molten metal of proper temperature for pouring and of the desired chemical composition.

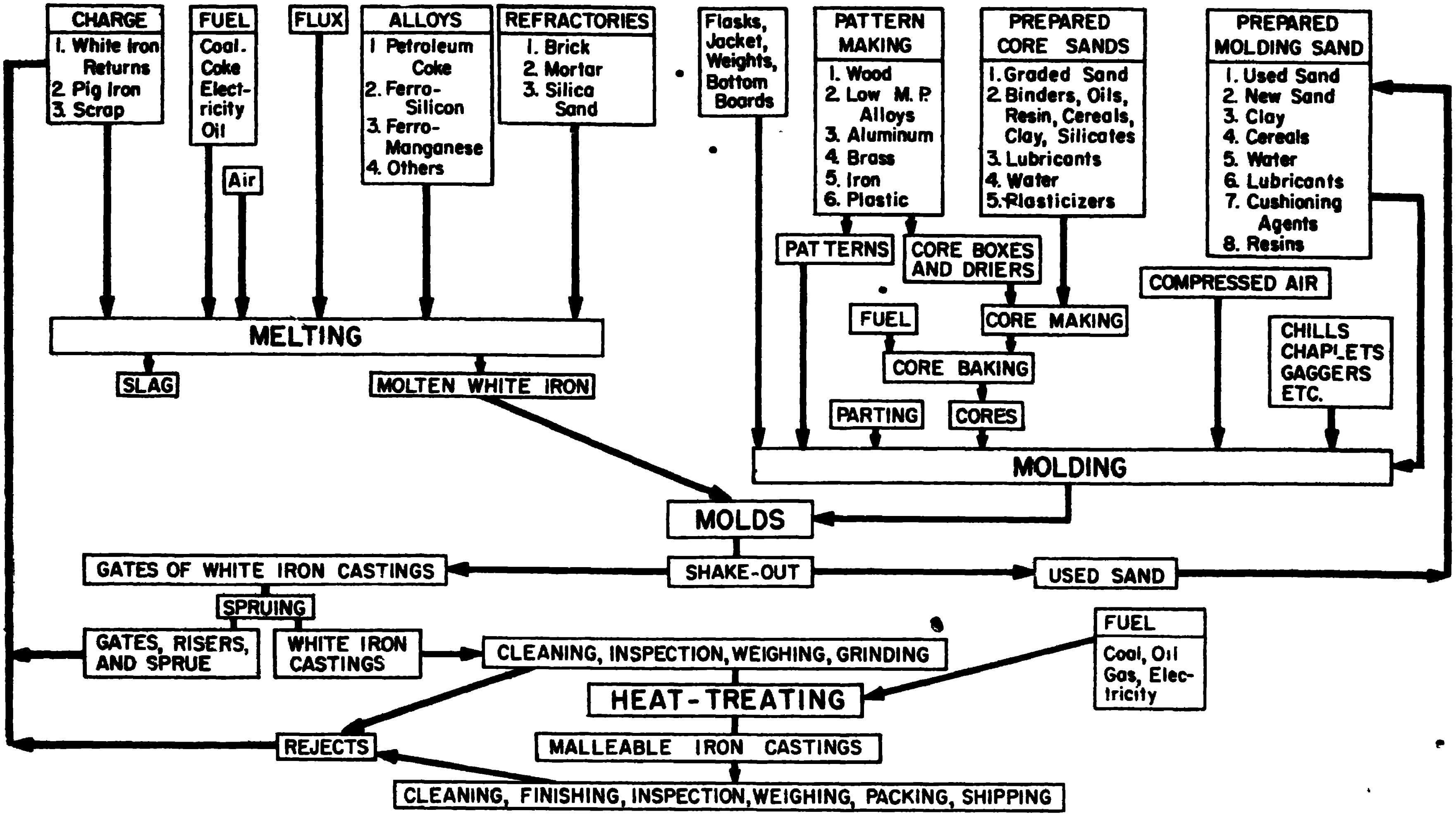


Fig. 1. **Flow chart showing various raw materials and fundamental manufacturing steps necessary for production of malleable iron castings.**

THE FURNACE

Most of the melting in malleable iron manufacture is done either directly in a horizontal-hearth furnace, commonly called an air furnace, or in an electric furnace – direct or batch melting – or by a duplexing operation in which the charge is initially melted in a cupola and the resulting molten metal is transferred to an air furnace or an electric furnace to be refined and elevated in temperature. Whether direct melting or duplexing is used is governed by the volume of metal required, and whether pouring must be on a continuous basis. For quantities up to about 50 tons per day, direct melting in an air furnace or an electric furnace is more economical than duplexing. For greater daily volume, duplexing is preferred, not only because of some economy in melting the large tonnage, but also because large production plants have continuous conveyor molding and must have metal continually available for pouring. As a result the greater proportion of the total tonnage of the industry is produced by this method.

The *air furnace* is simple in design, as the accompanying sectional view shows (Fig. 2), consisting essentially of a fairly shallow walled hearth in which the charge is melted by flame which enters at one end of the hearth and passes along above the hearth and into the furnace stack at the opposite end. Air furnaces are customarily fired with pulverized coal or with oil. The walls of such a furnace are of firebrick, supported and encased by cast iron or steel plates. The bottom, or hearth, is of either silica sand or firebrick. The top consists of a series of removable firebrick arches, called "bungs," which are held in place by adjustable metal frames. The bungs are rather flatly arched, their contour being calculated to reflect heat down upon the charge on the hearth, as a result of which the

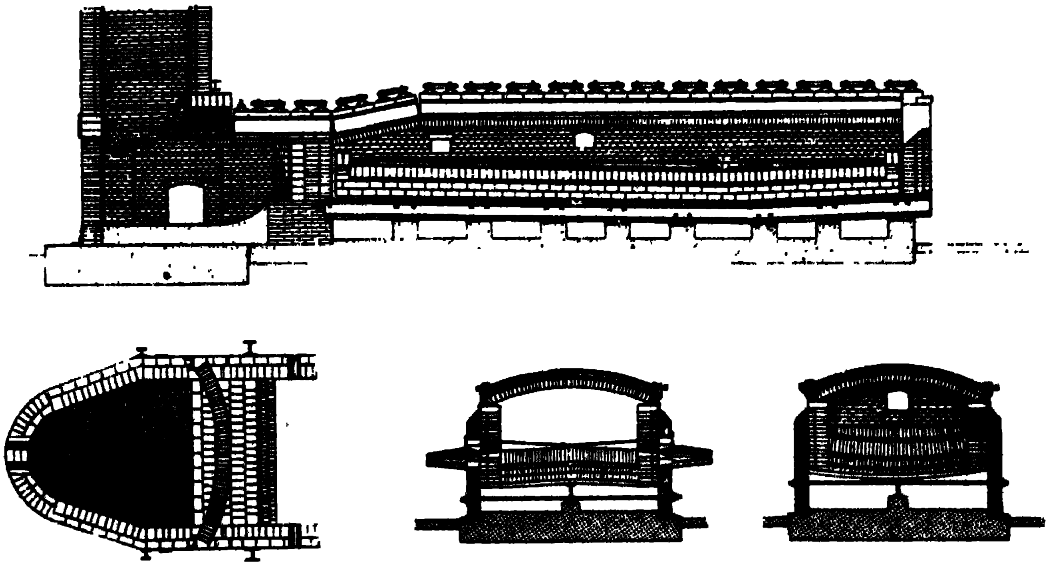

Stock End Top Hole Firing End

***Fig. 2.* Sectional view of typical air furnace.**

furnace is often called "reverberatory." The bungs are removable so that the furnace may be charged from the top.

The *electric furnace* is used in malleable iron foundries both for direct or batch melting and for the second phase of the duplexing operation. Furnaces of the direct-arc type are in almost exclusive use. A typical installation is shown in Fig. 3. Furnaces consist of a stout steel shell, circular in horizontal cross-section, with a bowl or cup-shaped hearth and a slightly domed refractory roof. Three graphite electrodes are employed in most installations, entering the furnace cavity through ports in the roof and usually controlled automatically. Melting of the charge in batch operation, or superheating and refining of the melt in the second phase of duplexing, is accomplished by arcs springing from the electrodes to the metal. Heating results from radiation from the arcs, contact of the metal with the arc, and to some extent from the passage of the current through the slag and metal, as well as from radiation from the roof and walls of the furnace. At one side, the furnace is equipped with a pouring spout; a charging door is generally situated opposite to it. Most such furnaces are of the tilting type designed to pour their contents into a ladle.

Fig. 3. **Direct arc type electric furnace used for duplexing malleable iron at the rate of 5 tons per hour. Metal is melted in a No. 5 cupola showing in the background. Note the trough used between the cupola and the electric furnace for the transfer of hot metal.**

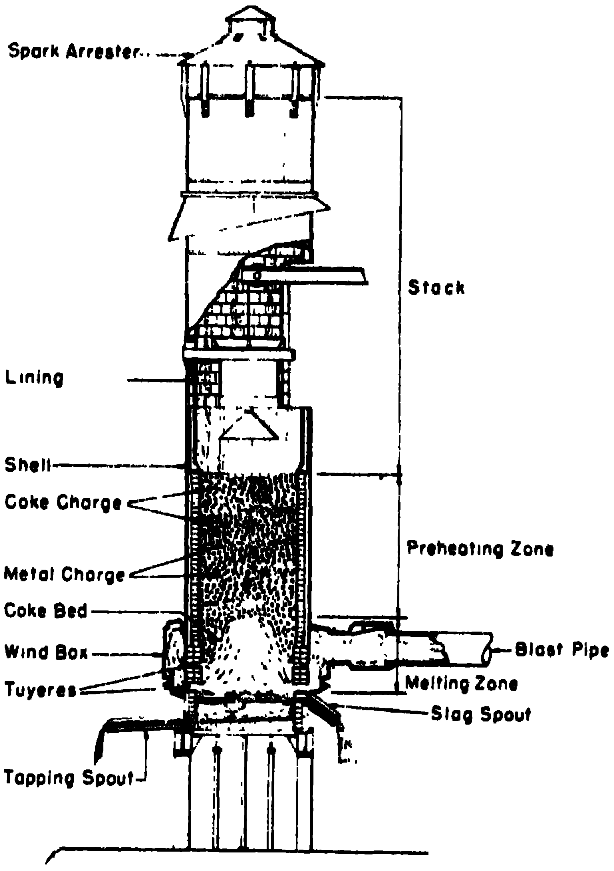


***Fig. 4.* Cutaway view of a typical cupola.**

In malleable iron manufacture, electric furnace capacities of two to ten tons are the rule. Since loss by oxidation is minimized, composition of the metal charged in batch melting is altered only slightly during the melting process. In the second phase of duplexing, the furnace is usually operated with the bath free from slag to avoid possible increase in the silicon content of the bath. Superheat temperatures up to 3000 degrees F., common in the malleable iron industry, are readily produced in these furnaces.[106,107,108,109]

The *cupola,* which is used as the first unit in the duplexing operation, is a vertical, cylindrical furnace, as shown in Fig. 4, built of steel plates and lined with firebrick or with monolithic refractory material. The lower portion is ringed by a wind box,[109,110,111] or air chamber, from which air blast enters the cupola through tuyeres to support combustion. A charging door, usually located some 20 feet above the bottom of the furnace, permits loading the cupola with fuel and the materials making up the charge. Cupolas in general use range from 30 to 90 inches in inside diameter. In charging, a bed layer of fuel—coke—is placed at the bottom of the cupola, with a layer of the other charge materials above it, and layers of coke and charge alternating thereafter up the stack of the cupola to a predetermined height below the charging door. As combustion proceeds, the molten metal may be drawn off directly, may flow into a forehearth for subsequent transfer to an electric furnace, or may run directly into the refining furnace.

The *refractory materials* used in lining furnaces, because of their chemical interaction with the materials of the charge as well as because of the extreme temperatures and the rough wear they must withstand, are of great importance in the melting operation. Many different types are used in malleable iron foundries. For the sides of air furnaces, modern high-duty or super-duty fireclay brick or a 60 per cent alumina brick is often installed. The density and maximum strength of brick for these installations are as important in service as its refractory qualities. The brick used in the bungs of air furnaces must be capable of withstanding severe temperature changes, must have high mechanical strength to sustain the pressure to which it is subjected in the frames, must not shrink or expand excessively on temperature changes, and must hold up under rough handling during the charging operation. Cupola furnaces are usually lined with standard firebrick and large blocks, which, when assembled, form segments of circles. The blocks and bricks are placed as closely as possible, and the joints between them are filled with a slurry of tory materials into place with compressed air.

THE CHARGE

The usual air furnace charge in malleable iron manufacture consists of pig iron, sprue (white iron, such as gates and feeders of castings from previous heats), malleable scrap, and steel scrap. These components should contain silicon, manganese, carbon, phosphorus, and sulfur in the relative amounts necessary to produce the desired composition. Allowances are made for oxidation loss of silicon, manganese, and carbon, and for some increase in sulfur during melting. A cupola charge for the first step in the duplexing process includes, in addition, coke as fuel and limestone as flux, with a reduced proportion of pig iron and malleable scrap. Typical weight charges for batch melting and for duplexing are:

	Batch Melting[*] *(Air Furnace)*	*Duplexing* *(Cupola)*
Pig Iron	25 to 35 per cent by weight	0 to 15 per cent by weight
Sprue	45 to 55 per cent	45 to 55 per cent
Malleable Scrap	5 to 20 per cent	5 to 10 per cent
Steel Scrap	0 to 10 per cent	25 to 45 per cent
Fuel		
Coke (lbs./t. melt)	0	160–240[†]
Coal (lbs./t. melt)	700–1,000	180–220[‡]
Electricity (kw per ton)	0	480[**]
Flux (lbs./t. melt)	0	60–80

[*] In electric furnace batch melting, the percentage of steel scrap is usually substantially higher and the percentage of pig iron substantially lower than these values.

[†] Depending on the design and operation of the cupola, and on whether hot blast is employed, the latter considerably reducing the coke requirement.

[‡] Where air furnace is second unit of duplexing equipment.

[**] Where electric furnace is second unit of duplexing equipment.

The reason for the low percentage of pig iron and the high percentage of steel scrap in duplex melting is that in the cupola the metal is melted in direct contact with the coke, thus picking up a large amount of carbon. Accordingly, it is not only unnecessary but undesirable to charge a substantial amount of high-carbon material such as pig iron. Steel scrap, being extremely low in carbon content, naturally provides a desirable melting stock. The proportions of the charge are varied according to individual foundry practices, particularly in duplex melting, and according to the quality and availability of scrap.

THE OPERATION

In batch or direct air-furnace melting, usual practice in charging is to distribute the sprue in a uniform layer over the entire area of the furnace bottom. Malleable and steel scrap are placed on top of the sprue, and the pig iron is charged last. Thus the smaller material is nearer the bottom so that the larger protects it from excessive oxidation. Moreover, the materials of lowest melting point are at the top, closest to the flame, so that melting proceeds from the top down, the pig iron melting and dripping down to alloy with the scrap and sprue and thus to lower the melting point of the total mass. In a furnace of average efficiency, a 25-ton charge is generally completely melted in six to eight hours. An additional two to four hours is required to superheat and refine the melt before it is tapped.

As the metal reaches the molten state, impurities in the original charge, ash from the fuel, any silica and clay eroded from the refractory lining, and resulting reaction products rise and combine to form a coating, called slag, on the surface of the liquid iron. This blanket of slag, which has an insulating effect, is removed at intervals through a skim door. Removal of the slag expedites superheating of the metal. All ferrous metals in the liquid state, when subjected to an oxidizing flame, first lose some silicon and manganese, and then carbon. Skimming off the slag exposes the bath more directly to the heating and oxidizing effects of the flame, and hence it is at this time, because of the higher temperature, that most of the carbon loss occurs. Determinations of chemical composition are made by laboratory tests during the melt-down to show what, if any, adjustments in silicon, manganese, or carbon are necessary to produce the desired white-iron analysis. Deficiencies in silicon are corrected by the addition of ferro-silicon; in manganese, by the addition of ferro-manganese; and in carbon, by the addition of petroleum coke or other carbon-bearing material. Conversely, excesses of these elements may be corrected through extending the refining time to permit further oxidation, through the addition of steel scrap to reduce the graphitizing tendency of the metal when cast, or in extreme cases through the addition of an oxidizing agent such as iron ore or pot or mill scale. Temperatures are regularly

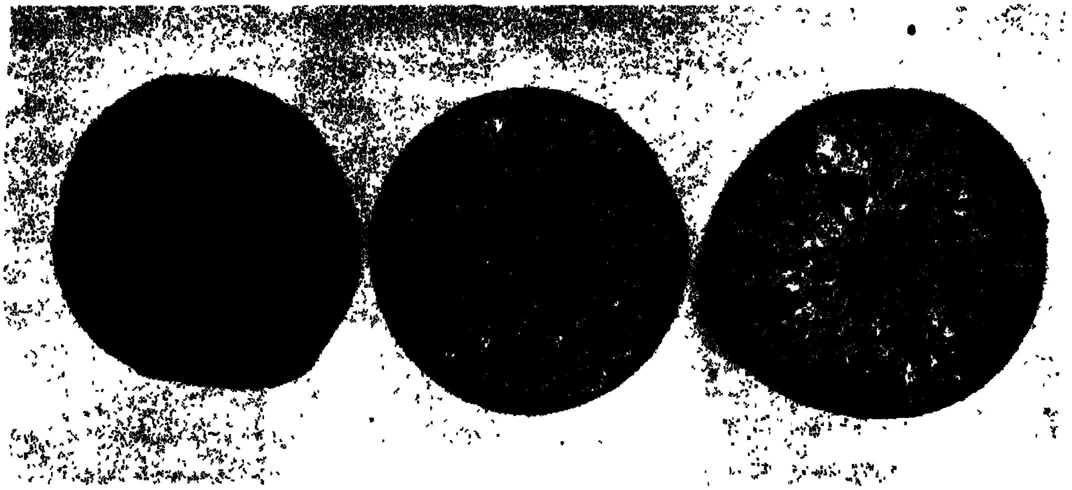


Fig. 5. Test sprues indicative of a heat of malleable iron. The sprue at the left, taken at the beginning of the heat, shows gray fracture. The slight mottling of the sprue in the center indicates that the heat is nearly ready for pouring. At the right is the pure white fracture showing that the iron is ready to pour.

checked through the use of optical, immersion, or automatic recording pyrometers. Atmosphere control is maintained either visually or by use of instruments. Test sprues such as those shown in Fig. 5 are poured, cooled, and broken to determine the progress of the heat toward a point where samples will no longer show mottling. The test samples are generally 1¾ to 2 inches in diameter. A "chill test" is commonly made to determine the time it takes for an oxide film to develop over the surface of a small spoon ladle of molten white iron. The elapsed time is indicative of the degree of superheat. In some plants, additional specimens are poured into special types of mold to measure fluidity. A specimen of this kind is shown in Fig. 14, Chapter XI.

In duplexing, the coke used as fuel in the cupola phase is low in ash and sulfur, high in British thermal units, and strong enough to support the weight above it in the cupola. Limestone or other fluxes are included in the charge to maintain low slag viscosity. Melting rates in this step of the operation vary from six to 45 tons an hour. In a number of instances, cupola operation has been greatly improved by the use of hot blast, which substantially reduces coke consumption. The hot blast, which is maintained at a temperature of 250 to 1000 degrees F., depending on the method of pre-heating, is derived in some installations from external sources which heat the air by means of oil or gas; in others, the waste gases from the cupola are used to heat the blast. A dehumidifier may be used to control the moisture content of the combustion air entering the cupola.

The second phase of duplexing, which may be carried out in either an air furnace or an electric furnace, is a balancing and refining operation. Its purposes are to assure the desired chemical composition in the final metal, to raise its temperature, and to attain the complete blending of components necessary to uniformity. This operation is vital because the molten metal coming from the cupola, where it has been in direct contact with fuel, is not suitably balanced in compostion and may have too high a graphitizing tendency. Hence, this second phase involves correction of deficiencies or excesses in silicon, manganese, and carbon during melting as in the direct refining described above in connection with regular air furnace practice. In addition, the operation increases the temperature of the melt by 15 to 250 degrees F., depending on the time the iron is in the secondary unit, the surface area exposed to the flame, the size of the melt, and the efficiency of the furnace operation. Uniformity of composition through thorough mixing also results. An inherent characteristic of acid cupola melted metal is generally a high sulfur content. In some installations, provision is made for reduction in sulfur by the use of a small intermediate container, in which measured quantities of soda ash are brought into intimate contact with the stream of molten metal issuing from the cupola spout and flowing into the second furnace.

SIGNIFICANCE OF CHEMICAL COMPOSITION

No discussion of malleable iron manufacture would be complete without at least a cursory consideration of each of those principal chemical elements which must be closely regulated during the processing of the metal, in order to develop optimum properties in the material.

Carbon. The fluidity of ferrous alloys is directly affected by the carbon dissolved in the molten metal. The higher the carbon content the greater is the fluidity. Containing some 2.0 to 2.6 per cent dissolved carbon, the molten white irons from which malleable irons are made are extremely fluid, thus making it possible to cast thin and intricate shapes, which would be quite uncastable in any of the low-carbon ferrous alloys. Higher combinations of strength and ductility and thicker mottle-free sections result from irons having carbon contents in the range of 2.0 to 2.35 per cent.

Not only does carbon influence fluidity in the molten iron, but, as temper graphite in the final product, it significantly contributes to the excellent machinability for which malleable iron has long been famous. Furthermore, pearlitic malleable iron owes its very existence to the ease with which carbon combines with iron to form strong, hard carbides. And, for the same reason, malleable irons may be hardened by heating to a sufficiently high temperature and quenching.

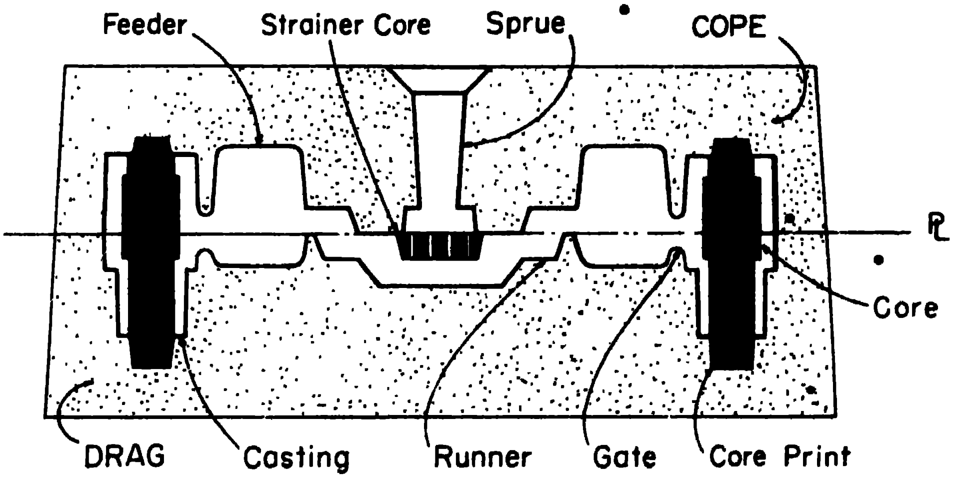
Silicon. Conversion of white iron castings to standard or pearlitic malleable iron by heat-treatment is markedly influenced by the silicon content of the white iron. If silicon is extremely low, conversion is difficult if not impossible.[5] If it is too high, graphitization occurs as the molten metal solidifies. The silicon content, hence, is carefully controlled, and in general varies inversely with the carbon. For example, an iron containing 2.40 per cent carbon and 0.75 per cent silicon has approximately the same tendency toward graphitization on solidification as an iron with 2.10 per cent carbon and 1.05 per cent silicon, for the same section size. The permissible amount of carbon and silicon in white iron, without danger of the formation of primary graphite, is always influenced by the rate of solidification. In thin castings a higher total of carbon and silicon can be tolerated than in castings of heavier section, since with lighter sections the solidification rate is greater and the tendency of the metal to solidify white is greater.

Manganese and Sulfur. Some sulfur is always present in the iron; due to a combination of the amount contained in the metal charged and the amount picked up from the fuel. Since sulfur retards graphitization, if present in large amounts, low-sulfur fuels are used and when necessary, manganese is added to form the harmless compound manganese sulfide. Carried as small inclusions both in the white iron and in the resultant malleable iron, this sulfide has essentially no effect on the properties or graphitization of the iron. In commercial practice an amount of manganese slightly in excess of that required to combine with all the sulfur as manganese sulfide is always used. When present in amounts markedly in excess of that necessary to neutralize the sulfur, however, manganese itself acts as a retarder to graphitization. Careful control of the manganese content is therefore essential.

Phosphorus. The white-iron composition for malleable iron castings normally contains 0.05 to 0.16 per cent phosphorus. This element is of advantage in somewhat increasing the strength of the metal. In the higher ranges, however, especially in conjunction with high silicon, it may have an adverse effect on impact resistance in low-temperature service and on hot-dip galvanized parts. Conversely, when silicon and phosphorus are low, the tendency toward galvanizing embrittlement disappears, as is explained in Chapter XI.

MOLDING

Molding, the second major step in the manufacture of malleable iron castings, consists of forming a cavity, which is an exact replica of the castings to be made, in a refractory material that in common foundry practice is composed of sand grains held together by a suitable binder. The process of molding first involves compacting the sand mixture in a container—the *flask*—around a *pattern* of the shape to be cast. Through appropriate design, the sand mass—or *mold*—is made so that it will separate horizontally into two parts to permit easy removal, or *drawing*, of the pattern from the mold. Then, when the two parts of the mold—the *cope* and *drag*—have been reassembled, a cavity remains within. Molten white iron reaches this cavity through the gating system, which consists of a vertical opening—the *downsprue,* horizontal distribution channels—the *runners,*—and constricted passages—the *gates*—leading to the mold cavity proper. Means for trapping sand and slag or for controlling the rate of metal flow may also be incorporated in the gating system. In order to compensate for the shrinkage that occurs when the molten iron cools and solidifies in the casting cavity, reservoirs—the *feeders*—are provided to supply molten metal to those parts of the casting that freeze last, thus assuring sound castings by preventing shrinkage voids from developing in the casting itself. Holes or cavities, required in the interior of the casting, are produced by suitable inserts, or *cores,* made of sand, which are positioned in the mold cavity where required by the design. Figure 6A presents schematically the structure of a mold, with cores in position and proper reservoirs, or feeders, together with runners and gates to assure the desired distribution of molten metal. Four factors are of chief concern in the molding operation; the pattern and corebox equipment from which molds and cores are made, the provision of adequate gating and feeding to assure soundness in the casting, the method of molding selected, and the sand used to form the mold. Figure 6B depicts schematically the several steps necessary to make a mold.



ig. 6A. Sectional view of a typical two-part mold, showing cope and drag, cores in place, casting cavity, sprue, runners, and gates.

PATTERN AND COREBOX EQUIPMENT

Patterns and coreboxes are made in accordance with the dimensions of the drawing of the part to be cast, with proper shrinkage allowance for the contraction of the metal during solidification and expansion during heat-treatment. The original pattern is generally made of wood and may itself be used as a working pattern for the production of sample castings. In the main, however, it is used as a master pattern from which metal working patterns are made. Single loose patterns, such as the original wood pattern, when used to make sample castings, require the molder to hand-cut in the sand of the mold the necessary gates, runners, and feeders. Since this is a slow process the usual practice is to attach elements to the pattern, which, when the mold is formed, will provide the

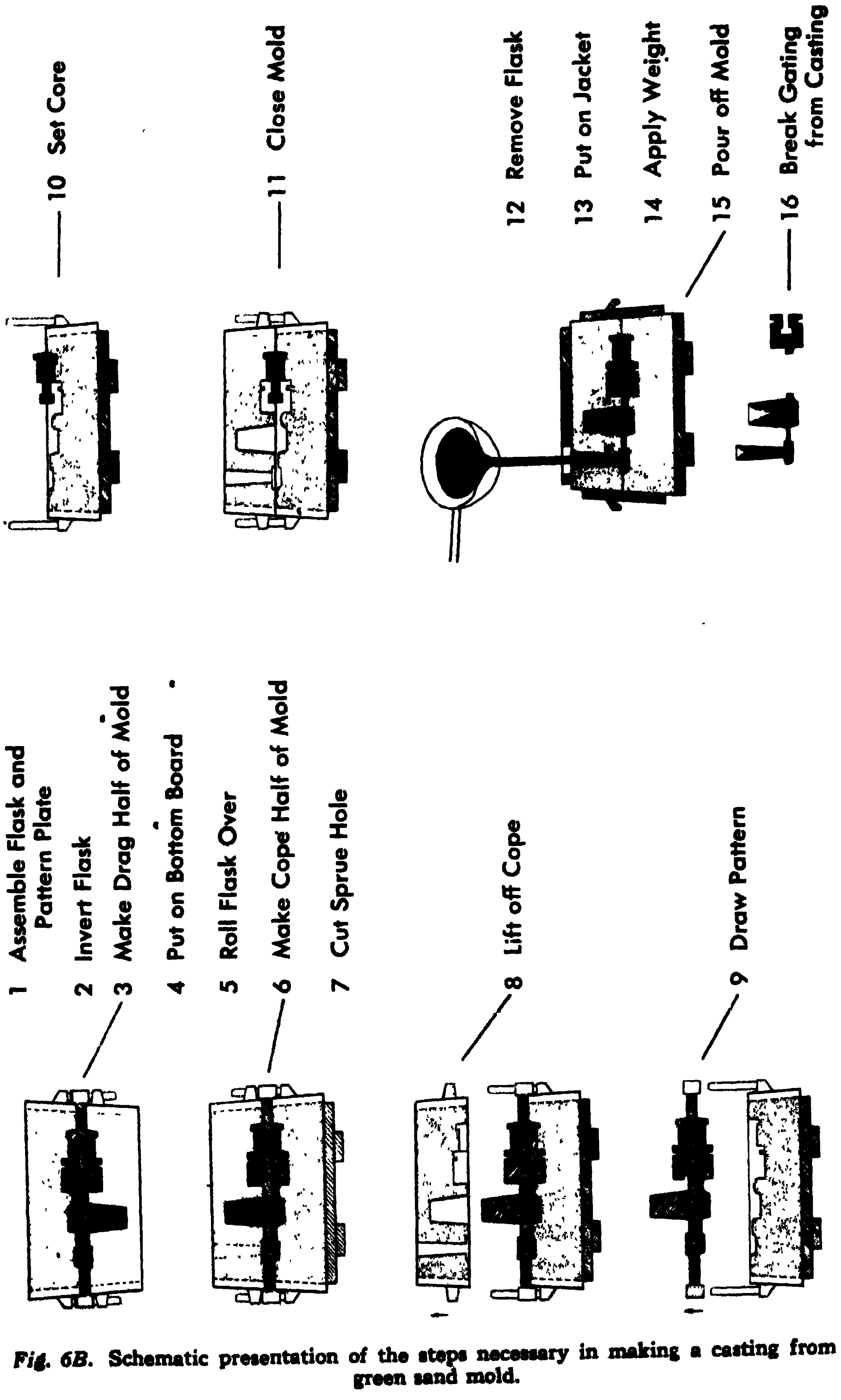


Fig. 6B. Schematic presentation of the steps necessary in making a casting from a green sand mold.

gating and feeding passages. For limited production quantities, several duplicate pieces may be attached to the same gating system. For larger production, matchplates or cope and drag plates, such as are illustrated in Figs. 26 and 27, Chapter VIII, are essential. Matchplates are metal plates with the components of the pattern affixed opposite each other on the top and bottom, to cope and drag faces, or, when the design allows, the entire pattern on one face. Cope and drag plates consist of separate plates and patterns for the cope and drag segments of the mold. Patterns are made of hardwood, aluminum, aluminum alloys, magnesium, and brass, and, for volume production, iron or steel. Questions of pattern design are discussed in Chapter VIII.

GATING AND FEEDING

Solidification of molten metal in a mold begins where the molten mass is in contact with the mold surfaces, a skin forming there and growing thicker as the liquid cools. Solidification progresses inward from the surface toward the center of the mass at a rate proportional to the square of the ratio of volume to surface area.[112,113] Thinner sections obviously will solidify before heavier ones. Moreover, the molten metal contracts while cooling in the liquid state, on changing from liquid to solid and while cooling in the solid state.[109] This fact means that the amount of metal, which in the molten state will fill a mold, will be insufficient to fill it after solidification. And since solidification is progressive from the outside toward the center, a void will develop in the interior of the casting unless additional molten metal is supplied.

Hence, as has been said, feeders are linked to the casting cavity by suitable channels. This additional feed metal must remain liquid until after the casting has solidified, in order that it may feed into the casting as contraction occurs. The size and position of feeders and the design and location of the channels or runners carrying metal into the casting cavity are therefore of extreme importance in molding. In the manufacture of malleable iron castings, gates and sprues are usually large in size because of the relatively high melting point of the metal and its relatively more rapid solidification as compared with higher carbon irons.[110,114] The objective of gating and feeding is so to supply molten metal to the mold, assure that the castings will be sound throughout, and to obtain the greatest number of castings possible from a mold of a given size.

METHODS OF MOLDING

The versatility of malleable iron is shown by the fact that commercial castings range in weight from a fraction of an ounce to several hundred pounds. Malleable iron castings, moreover, are generally made in large numbers of a single design. Hence, the industry has great opportunities for the use of mechanization and automation in its molding

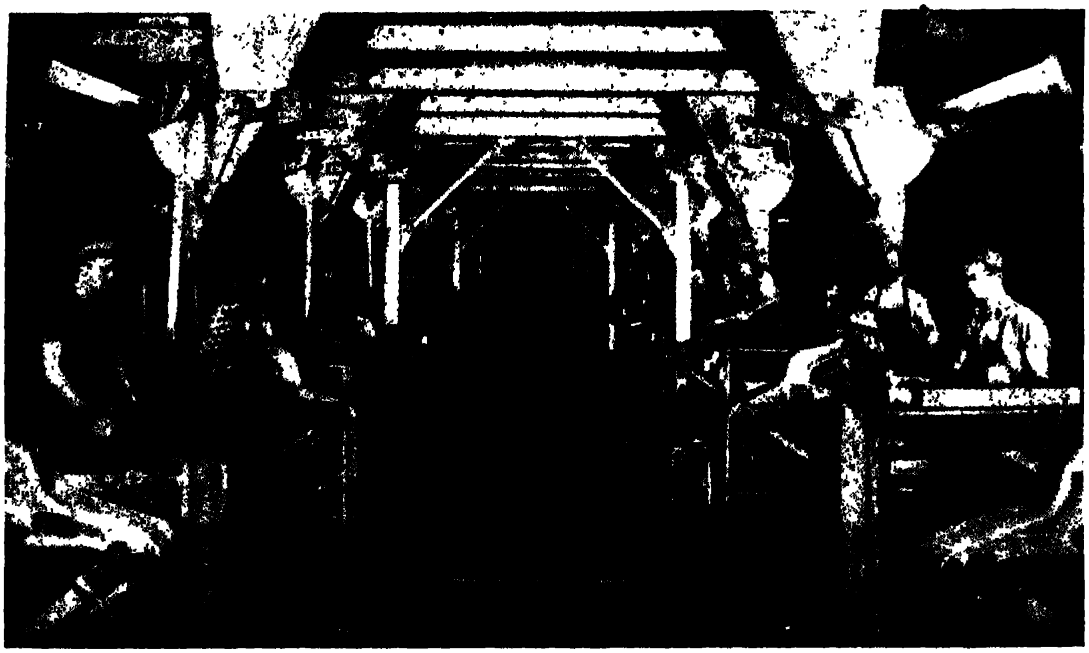


Fig. 7. **Line of jolt-squeezers using matchplate patterns.**

operations. Of the dozen or more basic types of molding, the two chiefly employed in malleable manufacture are green-sand and shell molding.[109,110,114]

Green-Sand Molding. Green molding sand is a mixture of sand grains, clay, water, and other substances suitable for molding and casting processes. It is called "green" because of its moisture content. Green-sand molding is the most widely used method in the production of castings, not only in malleable iron but in other cast ferrous metals as well. In the malleable iron industry, hand ramming of green sand about the pattern in the flask is rarely used, save for the production of small orders from loose or gated patterns or for short runs of large castings. Matchplate patterns are used with jolt-squeeze machines in medium casting production. (Fig. 7.) The machine settles the sand firmly around the pattern by jolting the flask one or more times and then further compacts the mass by squeezing a platen against the surface of the sand by air pressure. Medium and large molds generally employ two machines, one for the cope and one for the drag. A jolt-squeeze-stripper machine may be used to form the cope of the mold, jolting and squeezing the sand into place and thereafter freeing the pattern through the compressed-air actuation of pin lifts, which raise the cope mold from the pattern. The drag may be made in the same way, or by the use of a jolt-squeeze-rollover machine, in which, after the drag has been jolted and squeezed to compact the sand about the pattern, the pattern is then drawn by the lowering of the mold away from it.[109,115] Another method, with a machine called a sand slinger, is to throw the sand by centrifugal force into the flask over and around the pattern to form the mold. (Fig. 8.) In diaphragm molding, another green-sand method, pressure by compressed air is applied on one side of a rubber diaphragm

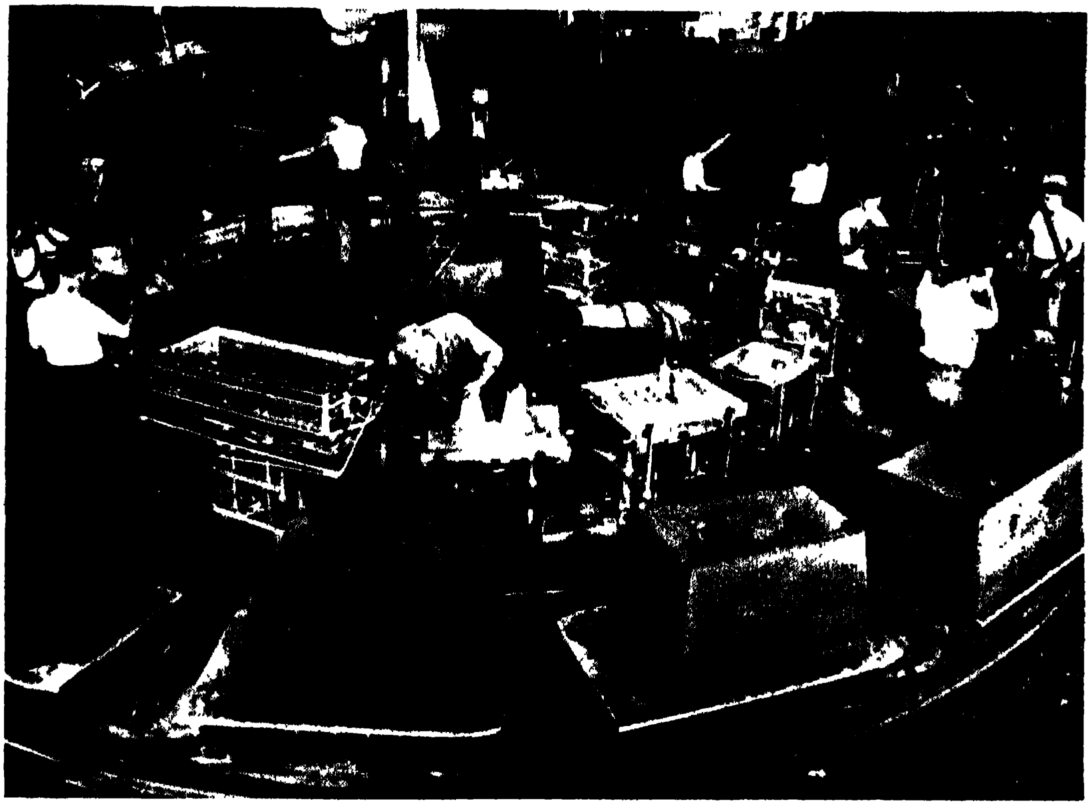


Fig. 8. **A fourteen station "merry-go-round" for the production of large molds. A small sand slinger (center background) is used to throw sand into the molds.**

placed over the face of the sand mass overlying a pattern in a flask. The diaphragm on the squeezer head of the machine adjusts itself to the contour of the pattern and, given a molding sand of sufficient flowability, the pressure is nearly uniform in all directions. With diaphragm molding, where the draw is deep, squeezing may have to be done in a succession of steps, either through a series of machines, or by the addition of sand to the flask after each of a series of squeezes.

The flasks used in green-sand molding are generally rectangular frames of metal consisting of two or more sections, the top one known as the cope, the bottom as the drag, and intermediate ones, if any, as *checks*. Pins and lugs are attached to each flask section so that when the mold is assembled it will be in correct alignment as the pins enter holes in the lugs. For matchplate molding and cope and drag molding of small to moderate size, removable flasks are in general use. One such is the snap flask, equipped with hinges at one corner and latches at the opposite corner so that it may be opened and removed from the mold. Another type is the slip flask, which is a rigid frame with smooth inner surfaces tapered four or five degrees from bottom to top for easy removal. When removable flasks are used, the mold, before being poured, is encased in a metal, wood, or asbestos-board frame known as a jacket to support it as the molten metal enters. Jackets for use with slip flasks have a corresponding taper. The other important type of flask is the rigid, permanent, so-called ***tight flask,*** which remains on the mold until after the casting is

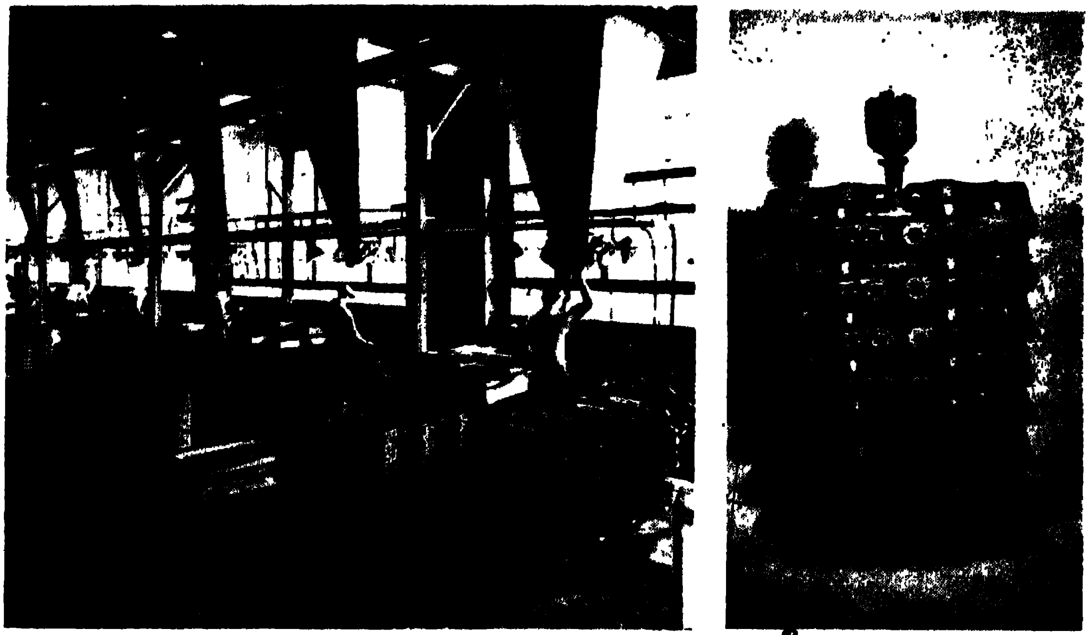


Fig. 9. **Stack molding operation. The cope of one mold acts as the drag of the one on top of it. A central sprue supplies metal to the entire stack.**

poured. One flask is required for each mold processed, and jackets are eliminated.[109,115]

The fact that malleable iron castings are often made in large numbers from a single design gives good opportunity for the use of multiple molding, or stack molding, an elaboration of the green-sand process. In stack molding,[116] pattern impressions are made in both sides of the mold, so that one side of the flask serves as the drag and the other as the cope when the molds are arranged in a vertical stack. One central sprue, by proper runners, supplies molten metal to the entire stack. As is shown in Fig. 9, flasks are stacked seven and nine high in one application, six and eight good molds resulting, since the impression in the upper face of the top mold and that in the lower face of the bottom mold are not mated with another cope and drag and therefore are not usable. The process is especially adapted to the production of castings for which relatively shallow copes and drags are suitable. In pouring, it is essential that a constant head and consequently a uniform flow of metal be maintained. The selection of the right type of molding machine is of great importance, for proper squeezing and packing are essential to the accurate forming of pattern impressions. Pattern plate surfaces must be parallel, and the accuracy of flasks must be carefully checked to assure the necessary precise alignment of the mating mold cavities. An advantage of stack molding is the reduction in the amount of sand required for the production of a given number of castings.

Shell Molding. In the shell molding process, a dry sand and resin mixture or a resin-coated sand is brought into contact with a heated metal pattern, maintained at a temperature in the range of 375 to 600 degrees F. by resistance heating elements under the pattern or built into the pattern itself, or by gas heating. Such a pattern is shown in Fig. 10.[117] The heat of the pattern causes the thermosetting resin of the sand mixture to cure partially, wherever it comes into contact with the hot pattern, thus forming a shell 1/8 to 1/2-inch thick, depending upon the time of contact, the temperature of the pattern, and the characteristics of the particular sand and resin employed. The thickness of the final shell is further controlled either by rotating the assembly some 180 degrees to permit the excess uncured mixture to fall away, or by allowing only a definite thickness of the sand mixture to come in contact with the pattern through the use of contoured backing plates.

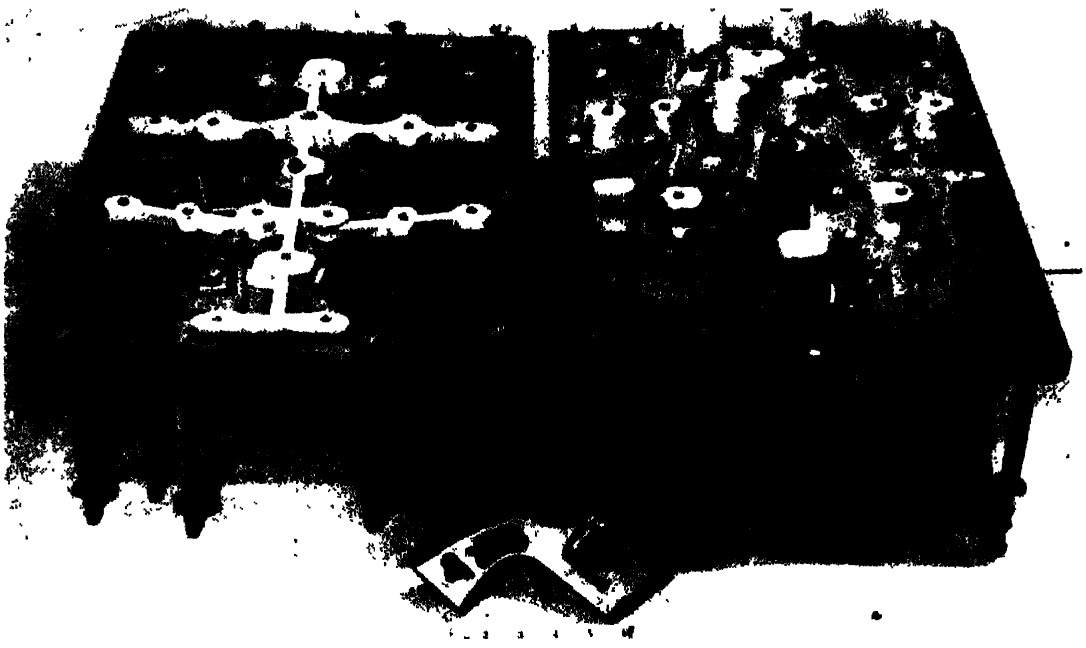


Fig. 10. **Pattern equipment used in a shell molding process.**

Completion of the resin curing is accomplished by using hot backing plates, by radiant heaters, or by transferring the sand-coated pattern to a hot oven. The cured shell is then separated—or "stripped"—from the pattern by appropriately located ejector pins, which extend through the pattern and push out against the shell uniformly when they are activated. The stripping is facilitated by a coating of silicone emulsion or wax release agent applied to the pattern prior to investment. Each shell may constitute a half mold, or a single shell may be separated into cope and drag portions which, when fastened together by being bonded with glue or resin binder in a closing fixture, will form the completed mold.

Shell molding is especially adapted to high-production runs and lends itself well to the manufacture of castings in which close tolerances are required, where it reduces machining. Excellent surface finish is inherent in the shell-molding process, which offers additional advantages because of its adaptability to mechanization. A representative installation

Fig. 11. **Four-station shell molding machine (right) and a four-station closing machine (left). This tandem set-up permits core setting and shell bonding immediately after making the halves of the shell mold.**

is shown in Fig. 11.

MOLDING SANDS

Because the major production of ferrous castings is in sand molds, sand is a foundry material of the highest order of importance. In the manufacture of malleable iron castings, green-sand molding continues the dominant method; sand control, both in the initial preparation of the sand and in the maintenance of its quality during use, is therefore a critical function in the manufacturing process.

Green-Sand Molding. Molding sands are made up of three or more ingredients. A green molding sand has as its principal constituent silica (silicon dioxide, SiO_2), together with clay and water. Other materials may be present in addition to these three basic ingredients, or may be added to the mixture to improve certain of its properties. Granular sand particles normally make up some 90 per cent of the mixture, and water from about 1.5 to 8 per cent. The clay, with a proper amount of water, gives the mixture its main strength and plasticity, acting as the bond or binder in the mixture. Water above the amount which the clay can absorb acts as a lubricant, making the mixture more plastic and more readily molded to shape. The average fineness of the sand grains determines the fineness of the mixture as a whole, and the shape of the grains influences many of the properties of the mixture. The properties which a molding sand must have for satisfactory service depend primarily upon these basic ingredients.

The properties of principal importance are flowability, green strength, dry strength, hot strength, permeability, thermal stability, and refractoriness. *Flowability* is a measure of the readiness with which the sand mixture will pack uniformly in forming a mold about the pattern by the jolting or squeezing process; this is critically important to the other properties of the mixture.

The next three properties are, first, the ability of the sand-clay-water mixture to develop strength as it is forced into shape during the molding process—its *green strength;* second, the ability of the mixture on the internal surfaces of the mold cavity to withstand erosion and pressure, after water has been driven off as steam by the molten metal entering the cavity —its *dry strength;* and, third, the ability of the dried sand-clay mixture thereafter to stand up against the pressure of the liquid metal against the walls of the mold cavity—its *hot strength.* (Fig. 12.)

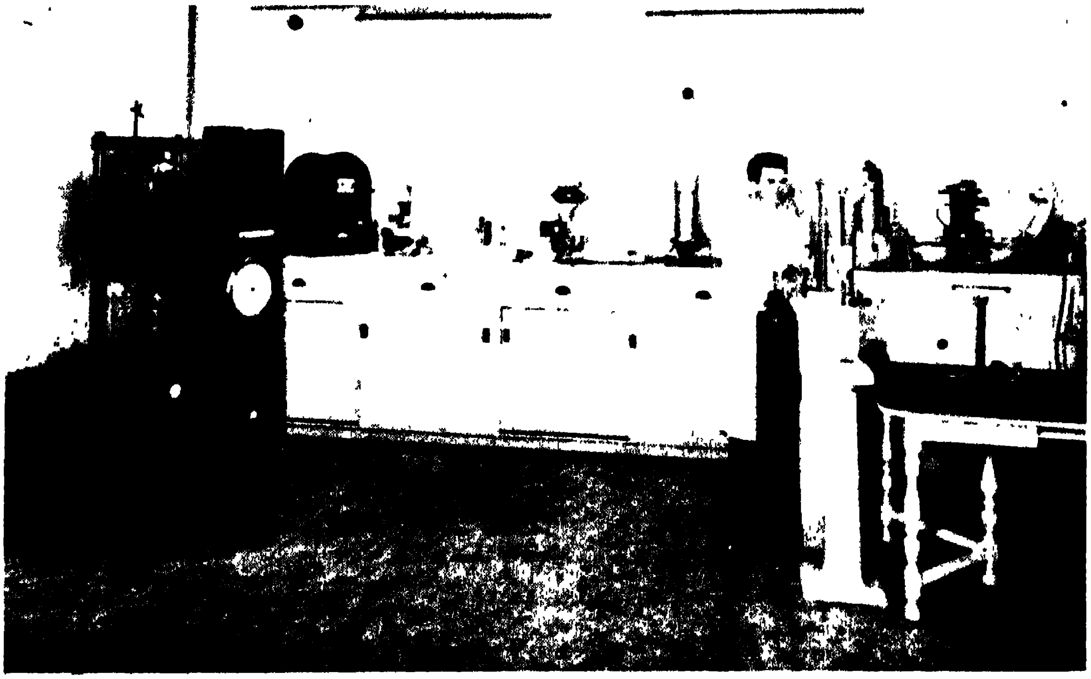


Fig. 12. **Partial view of sand control laboratory. On the left can be seen the dilatometer, on the workbench in the background is shown apparatus for checking strength, moisture and permeability of molding sands. The operator is testing a standard sample.**

The final three properties have to do directly with these three. Thus, the steam and other gases produced from the green-sand mold by the heat of the entering metal cannot pass off to the outer atmosphere, unless the molding sand mixture is sufficiently porous; its *permeability* measures its ability to release gases. The *thermal stability* of the sand mixture is its relative dimensional stability when rapidly heated, and determines whether the sand surface in contact with the hot metal will retain its shape and solidity or will crack and flake, with consequent defects in the casting. The *refractoriness* of the mixture measures its freedom from melting, softening, and sticking to the surface of the casting when subjected to the high temperature of pouring.

To improve certain properties or groups of properties, various additional ingredients often are added to green molding sand. The thermal stability of the mixture can be augmented by the addition of such materials as wood flour, ground cellulose, processed cereal hulls, and mineral perlite, an expanded aluminum silicate material. These substances serve to stabilize the sand mass by permitting the sand grains themselves to expand slightly as their temperature is increased through heat transfer from the hot molten metal entering the mold. A cereal binder, such as finely ground corn flour or fine corn starch, may be used for increased green strength; it also is useful in increasing the dry strength of a molding sand without risking the increase in hot strength which might be imposed by the addition of more clay. On those occasions where a gain in hot strength is necessary—in the production of some larger castings, for example—it can be secured by the use of more clay, such as bentonite, which is formed by the weathering of volcanic ash, or by the addition of silica flour, iron oxide, or ground pitch. In the manufacture of malleable iron, the most widely used additive is bituminous coal ground to a fineness greater than that of the molding sand itself, and known as sea coal. It is employed primarily to improve the surface finish of castings and the ease with which they can be cleaned. Gilsonite, pitch, graphite, or proprietary hydrocarbons may also be used for the same purpose.

A representative malleable iron molding sand mixture is as follows:

1. Silica sand, 40 to 150 AFS grain fineness.*
2. Bentonite, southern and western; 4 per cent of sand weight.†
3. Sea coal; about 4 per cent of dry sand weight, or enough to maintain 4 to 5 per cent combustibles which will be burned out and increase ease of freeing the casting from the sand.
4. Moisture; in proper amount to make the mix workable—some 3 to 6 per cent.

Most large production foundries, and especially those making relatively heavy castings, now use synthetic sands in which a sand with a low original clay content is bonded with bentonite or another type of clay. In the conventional open floor foundry, sand which is to be placed next to the pattern and thus is to form the surfaces of the casting, is generally run through a sand muller and aerated prior to use. Sea coal is added in the muller. This sand is customarily called "facing sand." When it is necessary to distinguish between this and the sand which forms the remainder of the mold, the latter is referred to as "backing sand." In foundries using continuous conveyor systems delivering sand to molding

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* Finer sands are required for light castings where good surface finish is important; for heavy work, higher permeability is needed, so the coarser sands are used.

† Where used sand or natural-bonded sand is employed in the mixture the amount of bentonite added may be reduced.

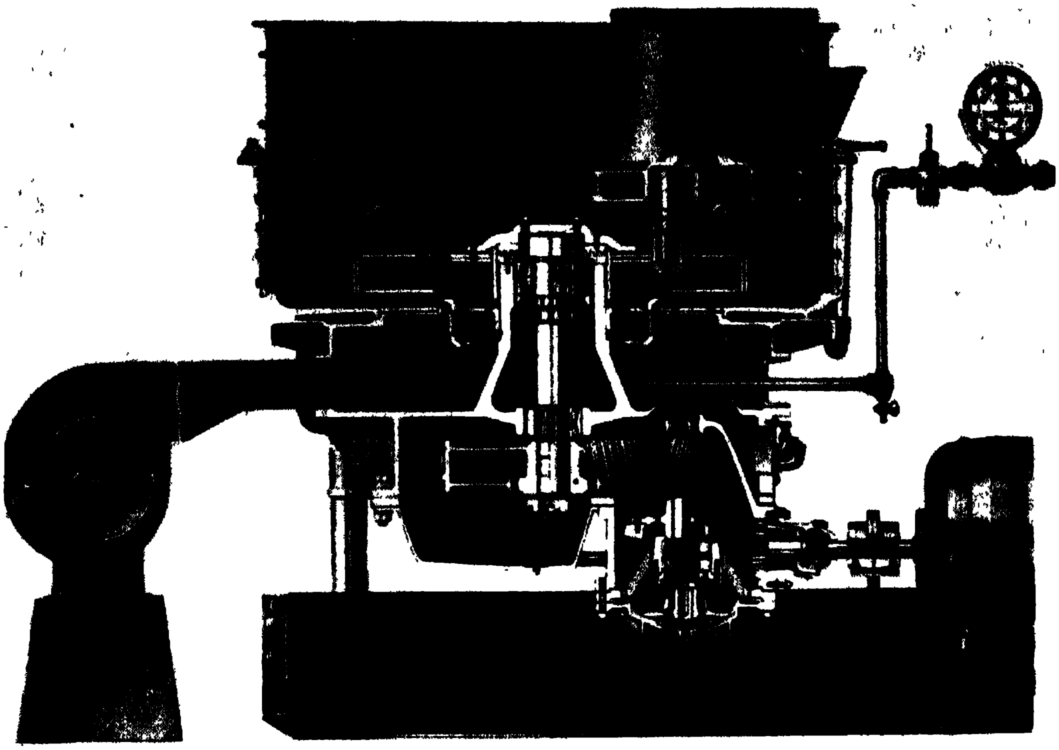

Fig. 13. Cutaway view of a high speed sand muller.

stations, all of the sand is mulled and aerated, so that the special facing sand generally is not required. (Fig. 13.)

Controlling the colloidal binders in molding sand by regulating the pH value, or hydrogen ion concentration, of the mixture has been found effective by malleable manufacturers. The pH value is a measure of the acidity or alkalinity of a substance, pH of 7 being considered neutral, lower values acid, higher values basic. Addition of a suitable chemical agent to the mix, changing the pH value, can substantially affect sand strength values. The addition of 0.015 per cent sodium carbonate to a normally acid molding sand, for example, was found to increase the pH from 6.30 to 6.78 and to raise the green compressive strength from 6.4 to 9.9 p.s.i.[118] Had other electrolytes been used, the results might have varied somewhat.

Pouring molten metal into molds affects the sand by burning out some of its clay content and driving off moisture, both of which are needed for bond that will permit the sand to form a sufficiently strong mold. In addition, pouring raises the temperature of the sand so that, unless it is cooled before being used again, it will be dry and crumbly. Broken cores and pieces of metal tend to accumulate in the sand, and continued re-use breaks down some of the sand grains into extremely fine particles which reduce the permeability of the sand. Before re-use, therefore, molding sands must be reconditioned. The steps usually included in the reconditioning following shakeout are: (1) cleaning by screening to remove bits of core and other refuse and by magnetic separating devices to remove stray pieces of iron, (2) removal of excess fines at shakeout and muller, (3) mulling, or thoroughly mixing the total mass, during which correct bond and moisture are restored, (4) aeration to reduce temperature and increase flowability. In side-floor molding, fines fall from the castings when they are shaken out and sprued. The main sand pile, following the addition of water and new sand or bond, is mixed, aerated, and cut into the molder's sand heap by means of a larger mobile, motorized sand cutter.

COREMAKING

Cores are made by ramming or blowing a suitable sand mixture into coreboxes, which are essentially permanent molds, having the shapes and dimensions of the cavities or openings which the cores are to provide in the metal casting. As a pattern is a shaped solid, the interior of a corebox is a shaped cavity. Core material must be highly refractory, since cores generally are totally surrounded by molten metal. In strength, the core must be able to withstand handling, yet not be so strong as to prevent normal contraction of the surrounding metal as it cools. Its properties of hardness and collapsibility are varied with the type of casting being made. It should break down or crumble once it has done its work of forming the desired cavity in the casting, and it should be so constructed that it may free itself easily from the casting during shakeout (Fig. 14).

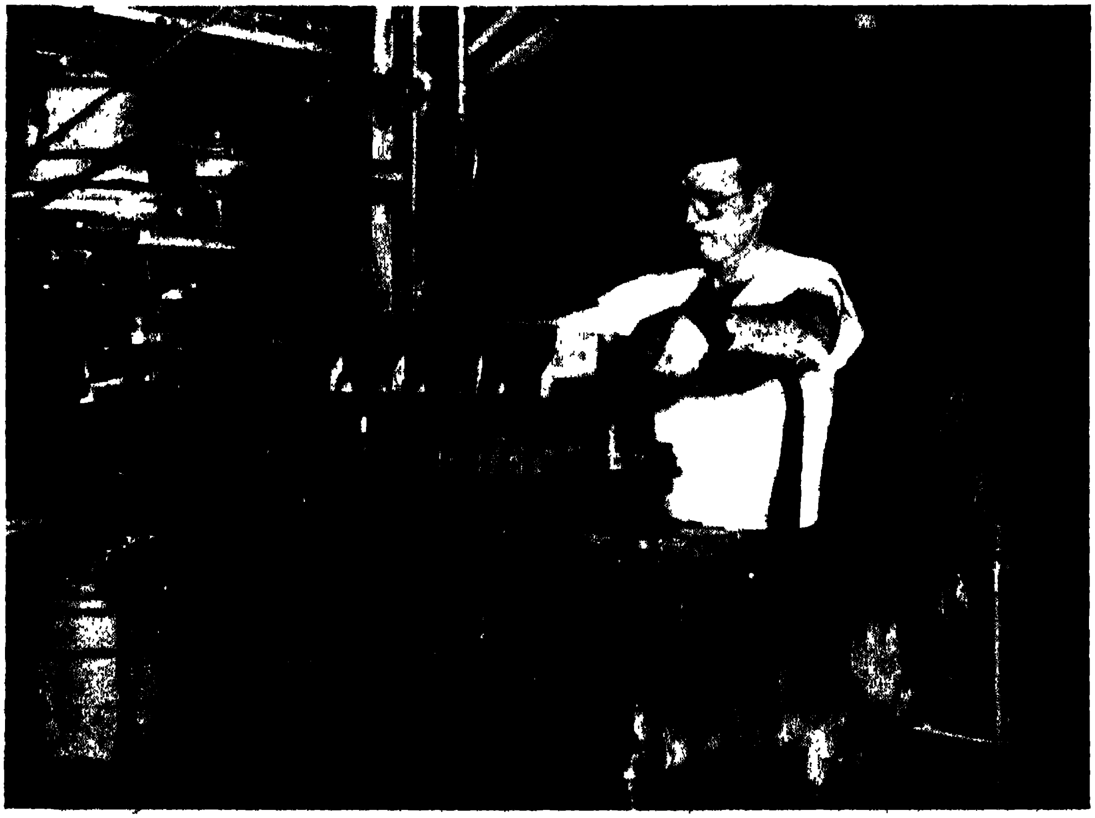

Fig. 14. Core blower from which the metal core box has just been removed. The operator is seen lifting the upper half of the box. The completed cores can be noted.

The material of which cores are made is generally sand of fine particle size held together by a binder. Binders in principal use are coal tar pitch or natural rosin, sugars such as dextrin and molasses, cereals such as corn flour, oxidizing oils such as linseed oil, thermo-setting resins such as urea formaldehyde and phenol formaldehyde, sodium silicate, and various clays such as bentonite. The mixing of sand and binder is done by either paddle mill or muller. A representative core sand mixture is as follows:

1. Silica sand, 25 to 160 AFS Grain Fineness.* (Average fineness usually about 75.)
2. Binders:
    (a) Dry strength: core oil, resin, rosin, et. al. (0.75 to 2.0 per cent of dry sand weight.)
    (b) Green strength: cereals (0.75 to 1.50 per cent), clays, fine bank sands.
3. Moisture: 2 to 5 per cent. (It is preferable to run as low a moisture as possible, and yet maintain adequate workability.)
4. Additives (optional, depending on the type of work being run, the method of making the cores, and the other sand mixture constituents):
    (a) for release: kerosene, light fuel oil, proprietary compounds —usually less than 0.75 per cent.
    (b) for collapsibility: wood flour (1 per cent or less)
    (c) for hot strength: iron oxide or silica flour
    (d) for plasticity: more bank sand, or sodium chloride.

Cores, if few in number, may be formed by the hand-ramming of the mixture into the coreboxes. Jolt and rollover machines are used as well, and for quantity production coreblowing machines are employed. These latter force the core mixture in a stream of compressed air into vented coreboxes (See Figs. 28 and 29, Chapter VIII), which allow the air to escape, but hold the sand in a firm, well-packed mass. Such cores are more nearly uniform than those produced by hand. Removed from the coreboxes; which are made in two parts to speed this operation, the fragile cores are placed on flat plates, or if not self-supporting, are placed in or on shaped containers, or supports, known as core driers, for the baking operation. This is done in ovens of either vertical or horizontal type at a temperature of about 400 degrees F. until the cores are thoroughly baked. (Fig. 15.) Those made with resin binders can be baked in dielectric-type ovens, in which drying times are in terms of minutes rather than hours. (Fig. 16.)

Cores may also be made by the shell-molding process discussed on page 226, or by a process which involves the rapid curing of a sodium silicate and sand mixture by carbon dioxide and/or heat. The silicate-carbon

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* Finer sands are required for light castings where good surface finish is important; for heavy work, higher permeability is needed, so the coarser sands are used.

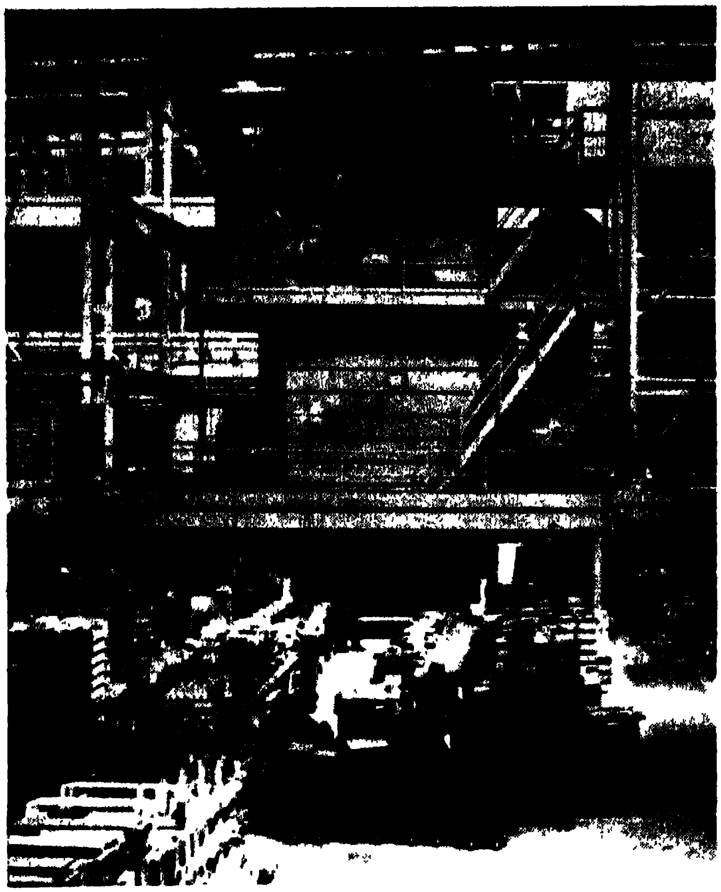


Fig. 15. Tower type core oven.

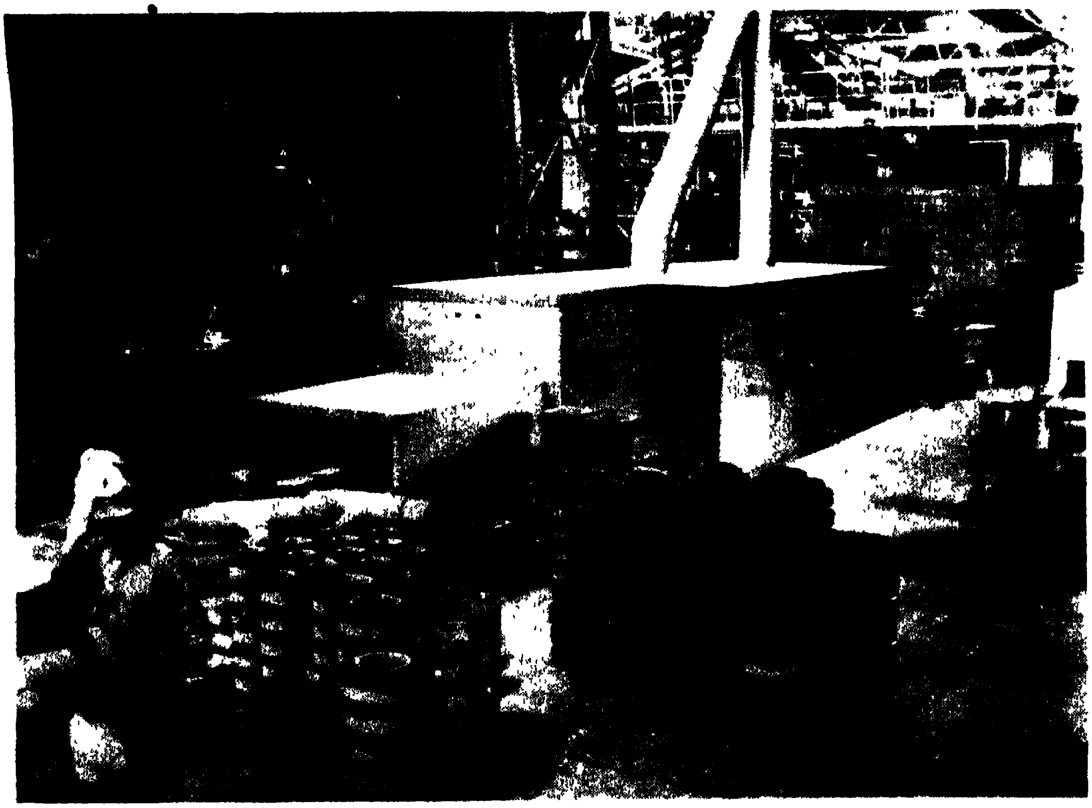


Fig. 16. Dielectric core oven having a capacity of over 8,000 pounds of urea bonded cores per hour. Total time on the conveyor is eleven minutes.

dioxide process, commonly known as the CO_2 process, employs sand coated with sodium silicate as the molding material. When this has been compacted into a corebox, carbon dioxide gas is blown into it, hardening the mass to desired strength, because of the chemical reaction between the silicate and the gas, whereby the silicate is converted into a strong gel binding the sand grains together. Organic additives are used in the mix for making cores burn out during casting, breaking down the binder, and assuring collapsibility of the core. The process makes possible the elimination of driers and is also used to some extent in making molds.

Both the shell-molding and the silicate – carbon dioxide processes eliminate the necessity for subsequent baking and for core driers. The cores made by these methods are more accurate because they are cured in the core box. Those made by the shell process, being hollow, have the advantage of ready collapsibility. Whatever the process, the cores, after inspection, are set in place in the molds, which after being closed are ready to be poured or filled with molten iron.

POURING

Pouring is the most dramatic operation in the foundry. Several methods of handling molten metal from furnace to mold are in common use. Iron may be taken from the furnace in overhead rail or buggy ladles, holding several hundred pounds, and then transferred to pouring ladles at a location near the respective pouring stations or floors, where it is either poured into the molds from the transporting ladles or transferred into smaller pouring ladles. These methods are feasible for both continuous and batch-type melting. In large production foundries, pouring stations are located on the conveyor line. (Fig. 17.) Pouring temperatures, determined by optical or immersion pyrometers, or by electronic radiation, range from 2600 to 2800 degrees F. During pouring, the walls of the mold are supported by the flask if a permanent one is used, by a wood or metal box called a jacket, or by metal bands. The top, or cope, of the mold is prevented from rising (due to the ferrostatic pressure of the molten metal) by being clamped to the drag or being covered with a heavy flat plate. After the molds are poured and the metal has solidified and is sufficiently cool, the castings are shaken out of the sand. In some foundries, shake-out is done manually. In others, mechanical shake-outs are employed, being placed at the end of the conveyor systems or at a central location. They consist of vibrating grilles through which the sand falls, and which retain the casting. Following shake-out by either method, the sand is reconditioned, and the castings move forward for sprue removal, cleaning, and inspection. (Fig. 18.)

Since the white iron castings, which are later to be converted to malleable iron by heat-treatment, are brittle as cast, gates, runners, and feeders are readily broken from them. Spruing may be done at the floor where

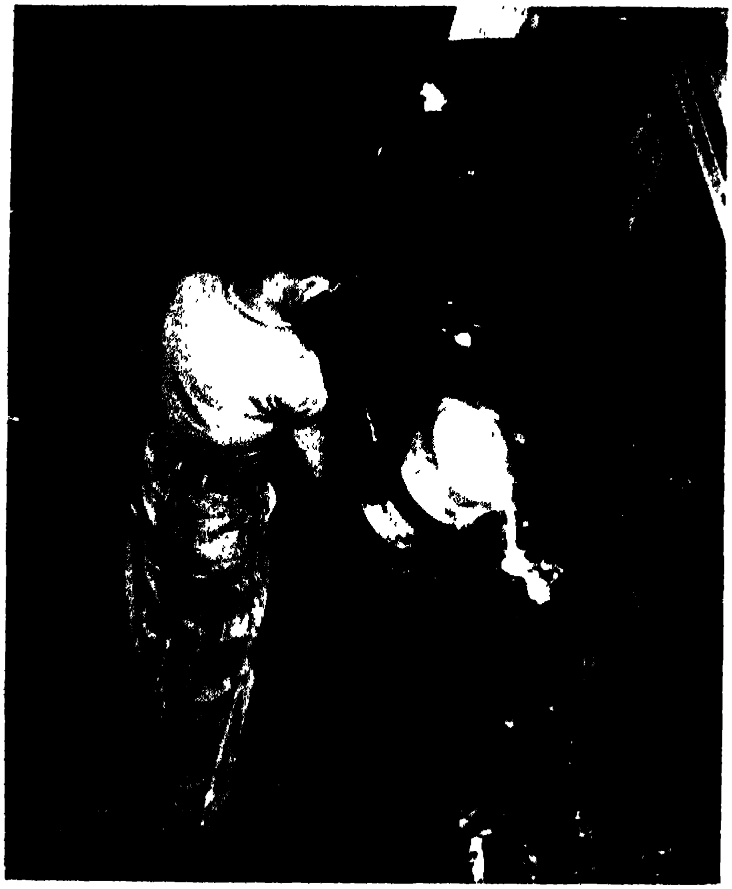


Fig. 17. Pouring off the mold. Note the location of the pouring station on a conveyor line. The operator tilting the ladle moves with the conveyor on an endless belt.

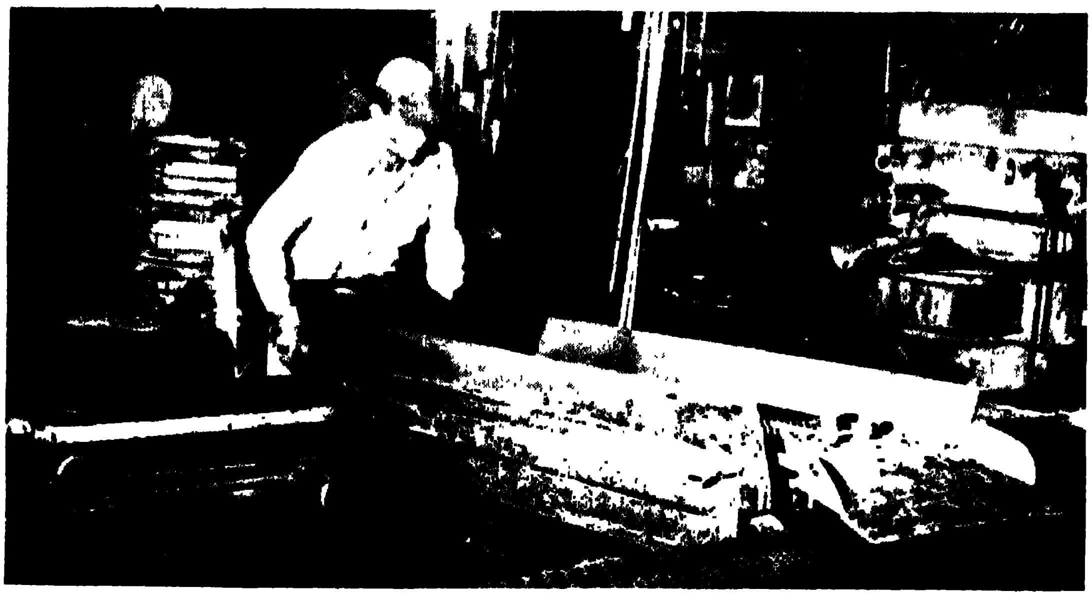


Fig. 18. The poured molds travel around the conveyor loop to the shake-out station. There, they are lifted from the cars and dumped. Castings slide across the vibrating shakeout grid directly onto a hot casting conveyor, which carries them to the cleaning department.

the castings were poured, at a central spruing location, on a conveyor belt, or in a spruing mill where rotary tumbling effects nearly complete removal of the excess metal. (Fig. 19.)

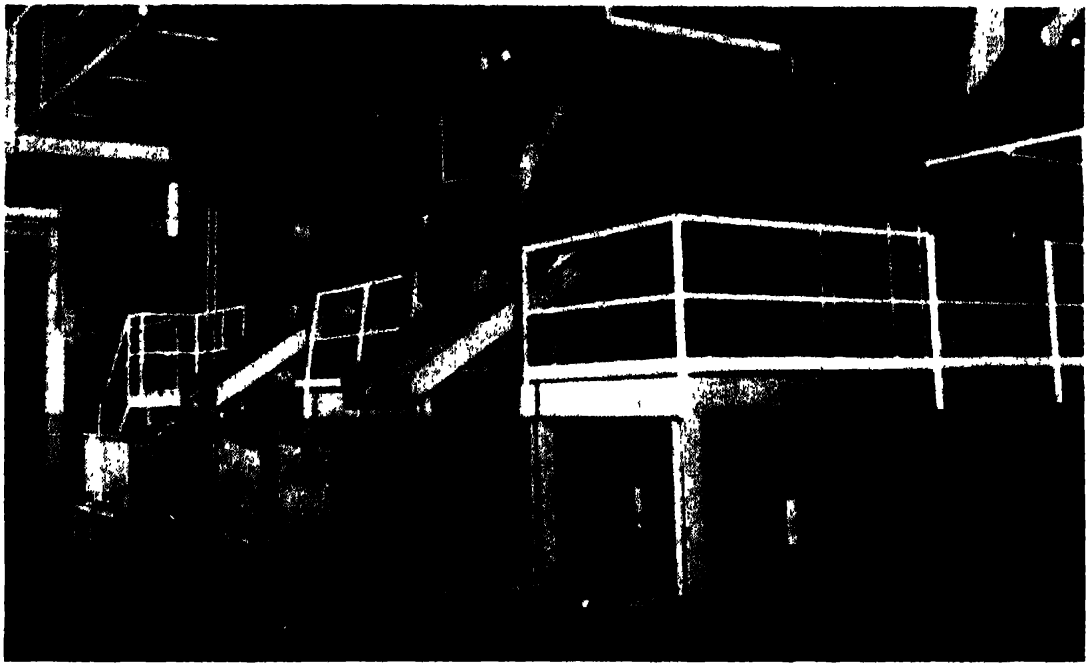


Fig. 19. Two 48" continuous rotary tumbling barrels.

HARD IRON CLEANING AND INSPECTION

The white iron castings may be cleaned by tumbling or by sand-, grit-, or shot-blasting to remove sand from the surface. They are then inspected for imperfections resulting from irregularities in molding or pouring, and are weighed or counted for control purposes. Light gate connections and any fins at parting lines are removed by chipping or grinding, silicon carbide wheels generally being used. Grinding before heat-treatment, or hard-iron grinding, as it is called, is usually restricted to small castings and to other castings which do not have large gates. The castings thereafter are transferred to the heat-treating department for conversion into standard or pearlitic malleable iron products.

HEAT-TREATMENT

Annealing Standard Malleable Iron. Annealing furnaces are of either the batch or continuous type. Batch furnaces include pot, muffle, car, elevator, and bell types. They are heated by pulverized coal, oil, gas, or electricity. The tunnel car-type gas-fired furnace, and the roller-tray and roller-hearth type heated by electricity or by gas-fired radiant tubes, are charged at one end and discharged at the other end at regular intervals and so are known as continuous furnaces. (Fig. 20.)

In annealing, either the casting must be protected against an oxidizing furnace atmosphere, which causes scaling and decarburization, or the atmosphere in the furnace must be rendered non-oxidizing by sealing against air entry or by admission of regulated amounts of externally generated gas. This gas either is reducing relative to the charge or is neutral and hence is employed to purge out the oxidizing elements of the furnace

Fig. 20. **An overall view of loading end of an electric, continuous annealing furnace.**

atmosphere. The castings may also be protected against an oxidizing atmosphere by being loaded in covered containers or pots. When it is necessary to support the castings to prevent distortion, an inert packing material, such as sand or gravel, is used. Packing increases the mass to be heated, reduces the readiness of heat transfer, and therefore lengthens the annealing time. (Fig. 21.)

The pot-type batch furnace, which is built of firebrick, is well insulated, and is direct-fired by coal, oil, or gas, generally holds an average of about 40 tons of castings packed in stacks of iron pots or iron boxes, or in stacks of open rings within which packing material is used to support and protect the castings.[120] If pots and packing are used, the total annealing cycle in a representative furnace of this type is 120 hours; when packing rings are separated by plates, or pots with bottoms are used, and packing can be omitted, the cycle is reduced by about 24 hours. Fans inserted in a secondary wall at the firing end of the furnace may be employed to even out temperature gradients and secure uniform heat distribution throughout the furnace, thereby reducing the over-all time requirement. (Fig. 22.)

Pots and packing are not necessary in batch furnaces heated by electricity. Trays and baskets are used to facilitate handling and to support castings during heat-treatment. The electric furnace, being sealed, generates its own highly reducing atmosphere; the castings hence require no protection. In some radiant-tube furnaces, a prepared neutral atmosphere is used to prevent scaling. In others, with the sufficiently tight seal provided by bell-type construction, it is not necessary.

The muffle-type batch furnace is essentially one refractory shell inside another, the inner shell enclosing a space sealed against the products of

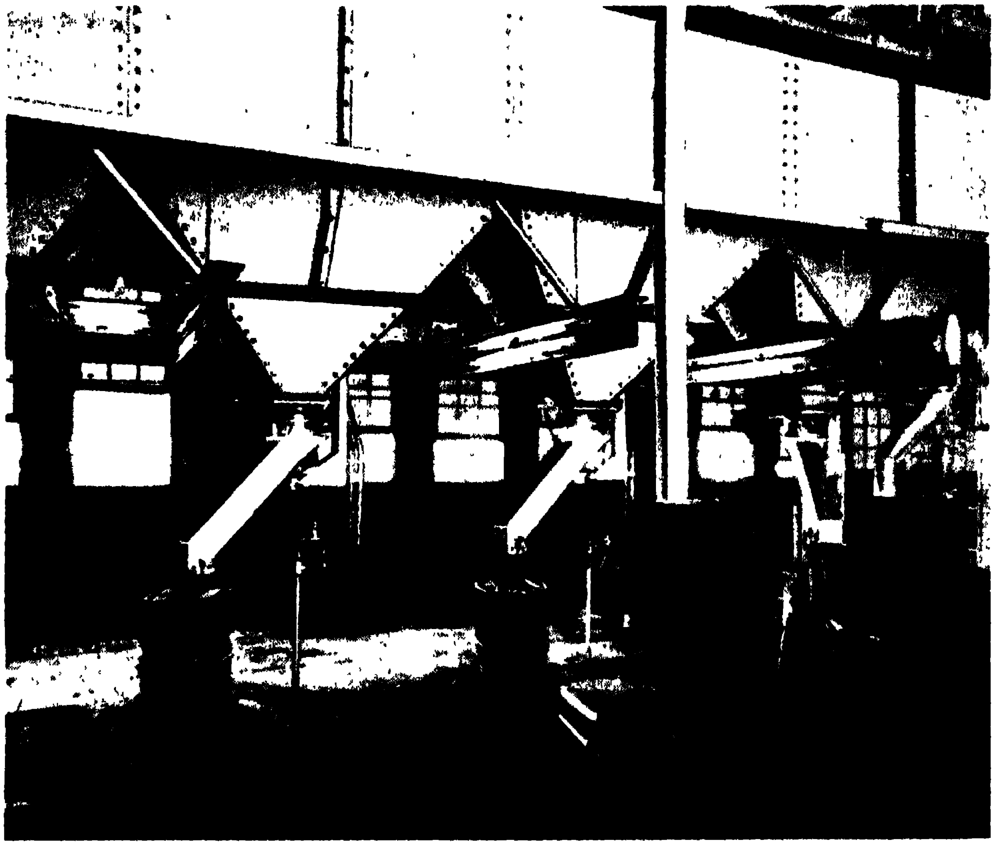


Fig. 21. Annealing pot packing station.

Fig. 22. Typical batch annealing furnace fired with pulverized coal.

combustion. Pots and packing material hence are not needed to guard the castings in this oven against oxidation. Cost of pots is eliminated, and a larger load of castings is annealed at a time. Oil or gas is used as fuel in these furnaces, in which the average annealing cycle—seven to ten days—is longer than that in pot-type furnaces, because of the additional time required for cooling the furnace and for loading and unloading individual castings.

Car-type batch furnaces, fired with oil, gas, or coal, are designed so that stacks, or stands, of pots containing castings are loaded onto cars that are moved into the furnace when it has been brought to a fairly high temperature. The cars may be removed for cooling, or may be quickly transferred to another furnace of lower or high temperature, and so the annealing cycle may be shortened by several days.[121] Elevator-type batch furnaces, generally electrically heated, may be used singly or in pairs to carry out the same basic idea. If a single furnace is used, the car loaded with castings is elevated into it and the furnace is then brought to high temperature. (Fig. 23.) After first-stage graphitization has been accomplished, the car and load are lowered for fast cooling to second-stage graphitization temperature, thereafter being returned to the furnace for the second-stage treatment. When such furnaces are used in pairs, the first is at high and the second at low temperature, the car loaded with castings being elevated into the high-temperature for the first stage of the

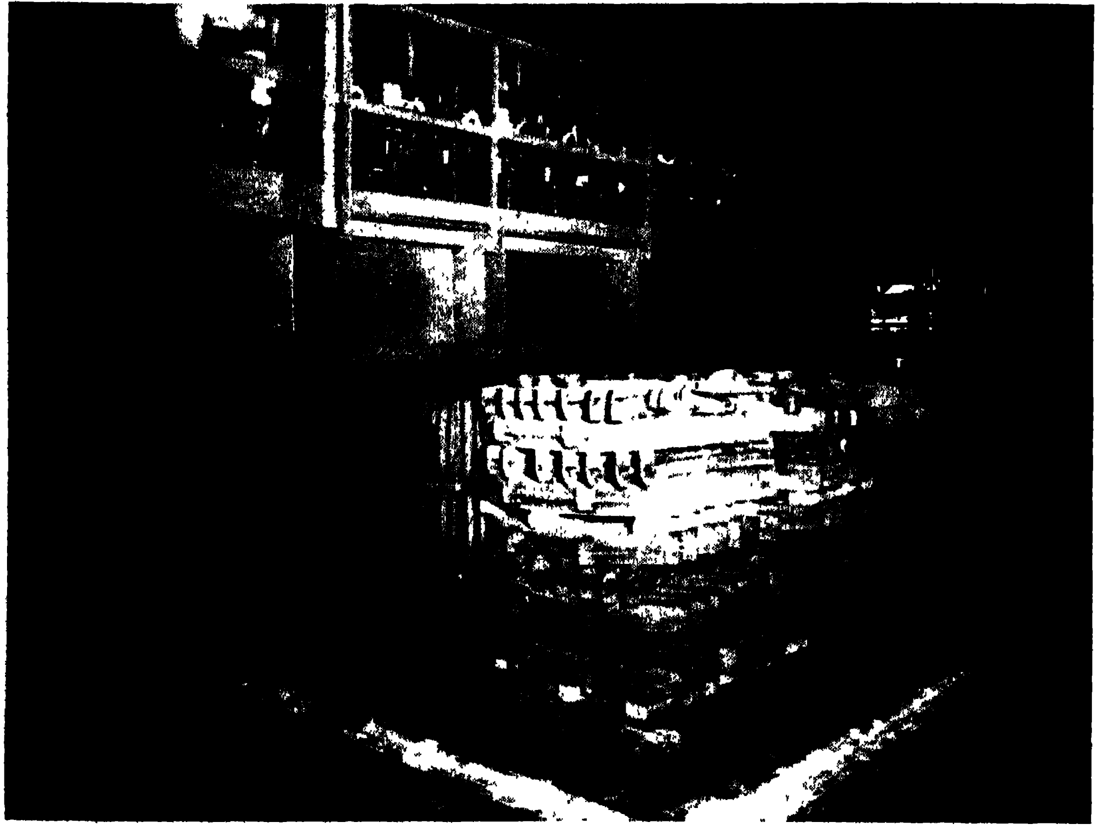


Fig. 23. Car type, batch muffle annealing furnace.

anneal and transferred to the low-temperature furnace for the second. Time and heat are thus saved, cycles being 48 to 72 hours. Continuous furnaces of the tunnel-and-car type, oil- or gas-fired, such as the Dressler kiln, have double-walled chambers, combustion occurring within a refractory muffle and hot gases being forced from one end to the other by a fan.[122] A car loaded with containers of castings enters at one end and moves rapidly into the high-temperature range. When the next car is pushed in, each car in the furnace moves one car-length forward. Cycles are normally from 72 to 120 hours.

In continuous roller-hearth furnaces,[123] heated by electric elements or by radiant tubes, the castings, loaded in baskets or trays, enter one end as white iron, pass through various zones of temperature, and emerge from the other end completely malleablized. Lacking the completeness of seal of the electric batch-type furnace, the roller-hearth continuous furnace uses small amounts of exothermic (heat evolving) or neutral gas to give a non-oxidizing atmosphere, so that pots and packing are unnecessary. Temperature control is extremely accurate, and only small quantities of castings are entering the various zones of temperature at a time; hence the annealing period is cut to a minimum (Fig. 24). In pusher-type furnaces, equipped with vestibules for loading and unloading to preserve the seal and maintain proper furnace atmosphere, processing is similar to that in roller-hearth installations.

The continuous furnaces shorten the annealing time for several reasons: Since the castings are loaded in relatively small lots—for example,

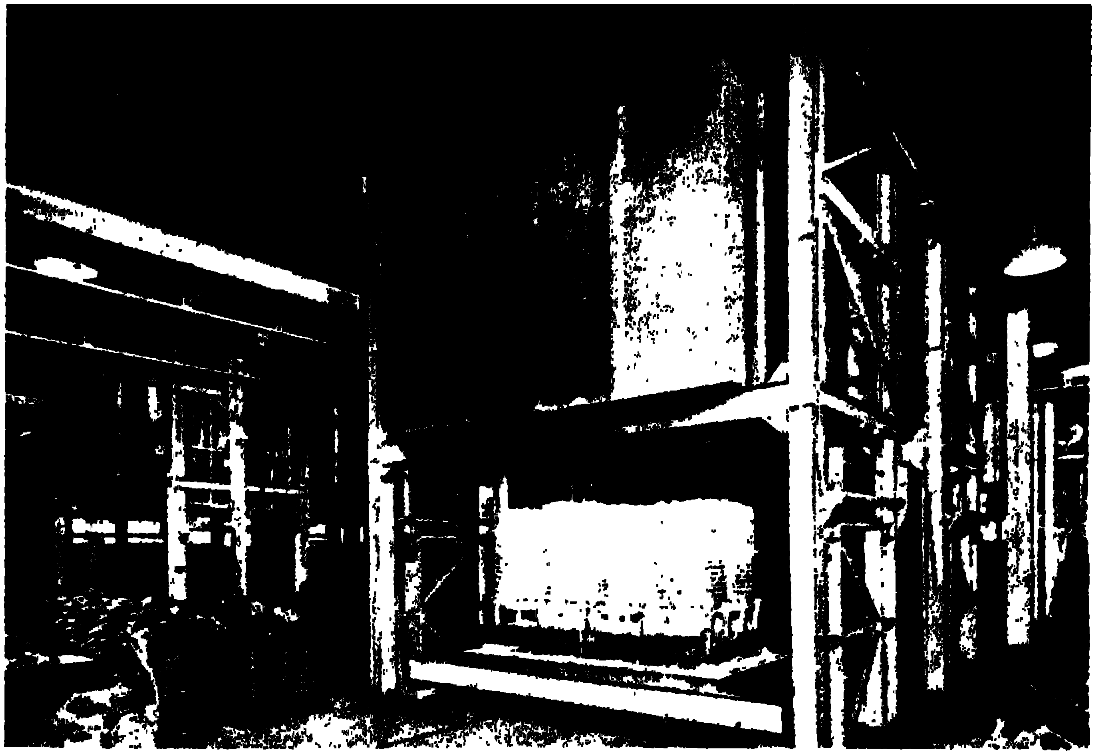


Fig. 24. Two-stage, batch type, elevator electric furnace.

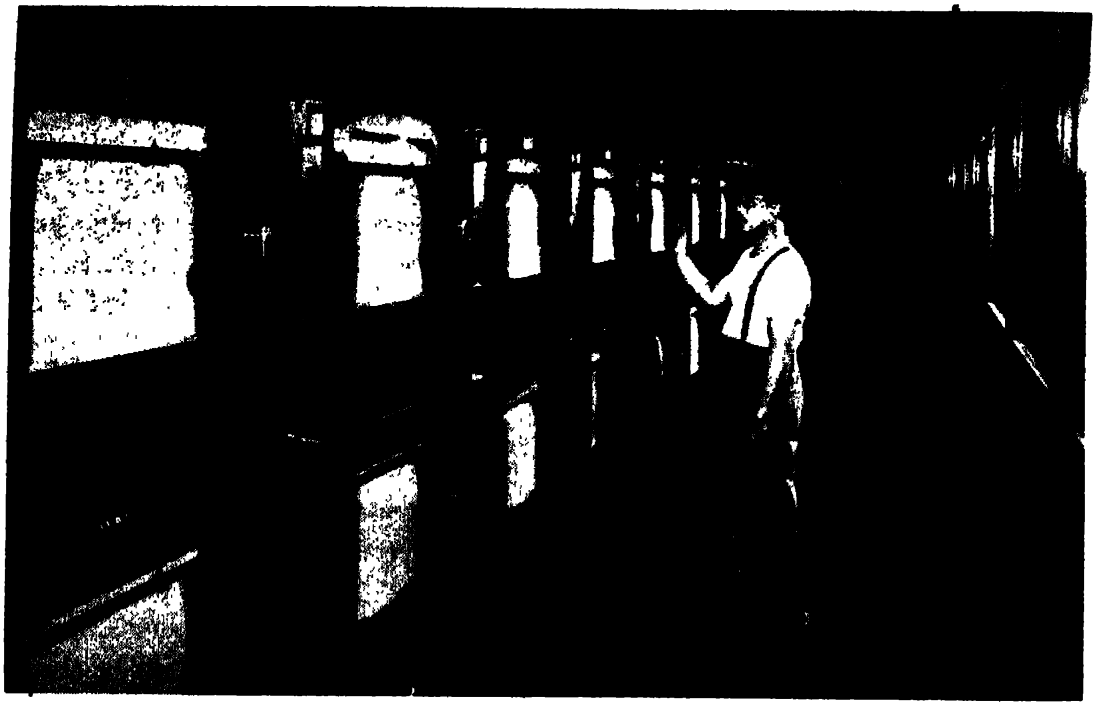


Fig. 25. Partial view of the control panel for a large continuous annealing furnace installation. Each pyrometer accurately controls and records the temperature of one particular zone.

500 pounds as compared to four tons or more in batch operation—and since heavy containers are absent, the time necessary to bring the castings to high temperature is cut; first-stage treatment is shorter because of the smaller lots and because of the high temperature used. Cooling to the critical range is also faster, and a shorter second-stage is made possible by the easy attainment of uniformity of temperature with the smaller lots.

To accelerate the annealing operation, treating castings in small batches is generally preferred, in order to reduce the temperature lag between the outermost casting in the batch and the castings in the center of the mass. It is important that the temperature and atmosphere of the annealing furnace be accurately controlled, and that the composition of the castings as discussed in Chapter XI, "The Metallurgy of Malleable Iron," be such as to favor a short annealing cycle. Such methods have provided malleable foundries with the means for attaining a minimum annealing cycle in the order of 20 to 65 hours for continuous furnaces. Small, electrically heated batch furnaces with provision for rapid tray charging and discharging are also employed, with cycle reduced to 30 hours.

Heat-Treating Pearlitic Malleable Irons. The equipment and facilities generally used for the annealing of standard malleable iron are in the main adaptable to the production of pearlitic malleable irons. Certain supplementary facilities, however, may be employed for the reheating, quenching, and tempering relied upon in the conversion of white iron to pearlitic malleable, depending upon the method of heat-treatment used. Pit-type furnaces and quench tanks take on additional importance

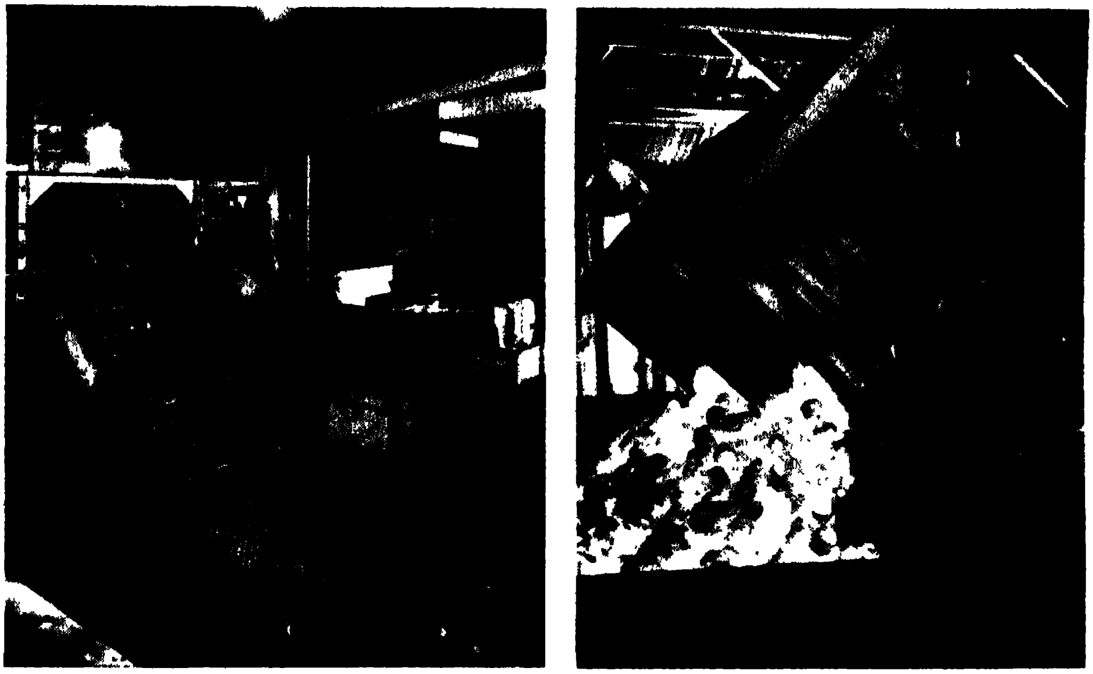


Fig. 26. **Pearlitic malleable castings leaving a temperature-controlled oil quench tank (left). A basket of hot castings is being dumped into the air quench chamber (right).**

in pearlitic malleable production. (Fig. 26.)

The pearlitic structure is secured in several ways, which are discussed in detail in Chapter XI. Three principal methods are: (1) arrested anneal, the method most widely used, which arrests graphitization by quenching, followed generally, by tempering; (2) heat-treatment of completely graphitized standard malleable iron; and (3) preventing or retarding second-stage graphitization through adding to the composition a suitable alloy, through quenching and re-heat-treatment, or through a combination of alloy and quench.

FINAL CLEANING, FINISHING, AND INSPECTION

After heat-treatment, castings are removed from the furnace, freed from packing, if used, and cleaned of any sand which may adhere. Many methods are used for cleaning the surfaces of castings. Tumbling, or blasting by shot, sand, grit, or water removes any sand or scale and leaves the castings clean for plating, painting, or any other finishing operations. (Fig. 27.)

Gates and irregularities not removed in the white-iron stage may be removed by grinding after the heat-treatment. Rubber- or resin-bonded aluminum oxide abrasive wheels are generally used. Where substantial gate connections are to be ground, the abrasive wheel cost is less if the work is done after the heat-treatment. Shearing, broaching, and milling sometimes offer advantages, in lieu of grinding, in removing gates from castings after heat-treatment. With pearlitic malleable castings, grinding is often done prior to final heat-treatment, particularly on surfaces which

Fig. 27. **A small direct motor driven, round tumbling mill. Tumbling removes sand and scale.**

are to be machined, since the grind may have a hardening effect. (Figs. 28, 29, 30.)

If a casting has become distorted through the relief of internal stresses or through improper packing during heat-treatment, it can readily be straightened either with hand hammers and forming blocks, by drop hammers, or in presses with special dies. Pressure of 100,000 to

Fig. 28. **Grinding of castings to remove gates and irregularities.**

Fig. 29. **Shearing of gates.**

Fig. 30. **The pads left by the gate and feeder connections on castings are often removed by a milling operation.**

150,000 pounds per square inch is employed to straighten castings of standard malleable iron. For coining, a permanent set of approximately 6 per cent must be imparted. This requires 60,000 pounds per square inch.[124] (Fig. 31.)

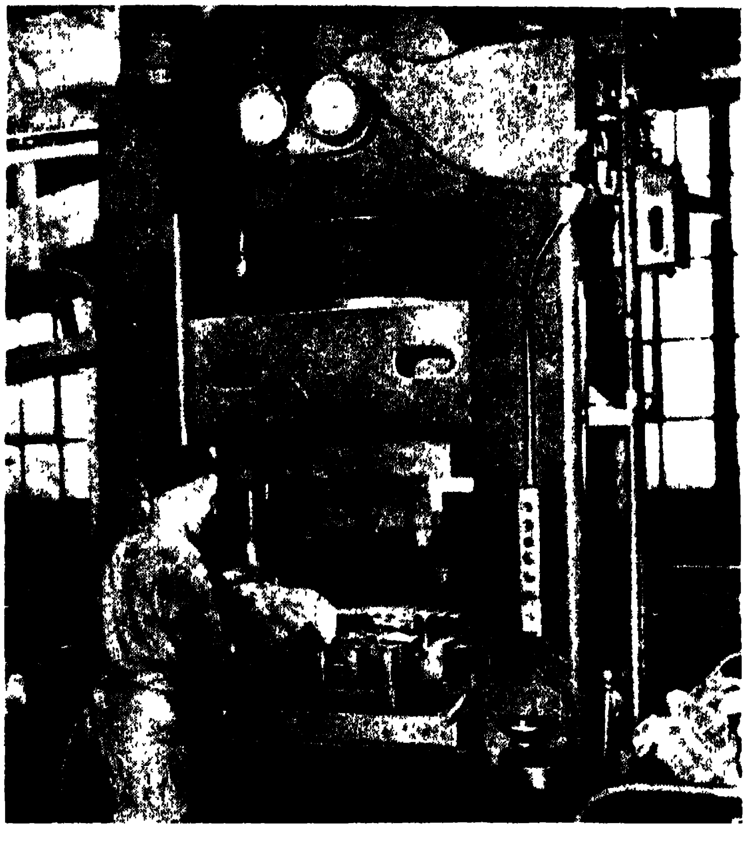


Fig. 31. **A hydraulic press applies pressure to a casting for the purpose of straightening within close limits.**

CHEMICAL, METALLURGICAL, AND RESEARCH PROGRESS

The many different operations involved in the production of malleable iron castings afford opportunity for frequent inspection at various stages in the process. Thorough final inspection, often including gaging, hardness testing, microstructure determination, magnetic or sonic testing, and other special operations, is also performed prior to shipment. Statistical quality control, which is applicable at various stages from melting to final finishing, is playing an increasingly important part in the production of castings, and has done much to effect economies and to insure improved quality in this field. Improvement in quality level of standard malleable iron and pearlitic malleable iron castings has been extremely important to engineers and has much to do with the increasing adoption of pearlitic malleable as a replacement for forgings and fabrications. The use of magnetic testing methods to detect surface imperfections, such as discontinuities, has contributed greatly to improving the quality and uniformity of the final product, as has the increased use of radiographic inspection of castings for subsurface irregularities.

Engineers are engaged in every phase of the foundry business. The Malleable Founders Society, the industry's national trade association, has been a supporter of the Foundry Educational Foundation since its inception, thus encouraging many graduate engineers from the best engineering schools in the country to enter the malleable iron industry. Control laboratories in individual foundries are the rule. Research programs of individual companies are vigorously supplemented by the activities of Malleable Founders Society, the Malleable Research and Development Foundation, and the Malleable Iron Division of the American Foundrymen's Society.

Through its Research and Technical Division, the Malleable Founders Society sponsors technical research, shop practice meetings for technical and operating personnel, arranges for plant visits which permit a free interchange of ideas between producers, issues Technical Bulletins on practical operating and metallurgical subjects, and annually sponsors a Technical and Operating Conference which is attended by all the leading metallurgists, engineers, and works managers in the industry. In addition, the Society maintains a staff of qualified men who are available for consultation with Society members and with customers to discuss design, quality control, or manufacturing techniques. The Society also maintains a laboratory in which it is in a position to do quality testing and otherwise assist members with operating problems of every kind. The staff members represent the Society on committees of the American Society for Testing Materials, the Society of Automotive Engineers, the American Foundrymen's Society, the American Society of Mechanical Engineers, and others.

To foster and encourage sound selling practices, the Malleable Founders Society is also active in the field of product promotion, maintaining a trade journal advertising program and a direct mail advertising campaign. Literature promoted in these campaigns is available to designers, engineers, students, and others who would like to have more information about malleable and pearlitic malleable iron castings. An accounting program designed to stimulate an interest in sound financial planning and control is carried on by the Society for the benefit of people in the industry concerned with cost finding, estimating, and related fields of activity.

For many years, the Society has carried on a safety program designed to reduce the number of lost-time accidents occurring in member company plants. There has been a substantial improvement in this record in recent years. The Society issues bulletins showing good safety practices, and otherwise undertakes to stimulate an interest in promoting the foundry as a good and safe place in which to work. Awards are given annually to the companies having the best improvement in their safety record for a given year as compared with the previous year.

X

MACHINING MALLEABLE IRON

MACHINING IS A CRITICAL OPERATION in the fabrication of castings into finished parts. Efficiency in the use of materials depends upon it, and it is often the determining factor between profit and loss in the total manufacturing operation. Machining procedures, from the choice of tool to be used to feed, speed, and cutting fluid, or coolant, must be guided first of all by the inherent characteristics of the material to be worked. With the iron-carbon alloys, of which the malleable irons are one group, this is another way of saying that machinability and machining procedures depend upon structure. Standard malleable iron has a ferritic structure. Its uniformity and evenly distributed content of nodular graphite or temper carbon are the reason why it can be machined with greater ease than any other ferrous metal of comparable properties. In the pearlitic malleable irons, it is generally held that if the combined carbon content of the structure is kept at the minimum or the combined carbon is kept in spheroidal rather than lamellar form, machinability rating will be high.

The common cutting medium for tools and drills prior to the 1890's was carbon steel. During the 1890's the science of cutting metals was revolutionized by the much higher speeds made possible through the introduction of the so-called high-speed steels. In the 1920's, carbide-tipped cutters became important in the machining of cast iron. Since then, further refinements of these tools have raised the limiting value of hardness for normal machinability to a considerable extent. Machining with carbide tools has been greatly facilitated by the use of interchangeable "throw-away" inserts, available in a range of dimensions, each with several cutting edges which can be utilized before discard. The advent of oxide (particularly alumina) and tungsten boride cutting inserts for some uses has greatly increased speed of machining and improved surface finish. Carbon steel tools are still used for certain purposes, but may be disregarded when machining from a production standpoint is being considered. The relative values of the four cutting materials in terms of cutting speed are indicated by the following ranges for turning operations, depending upon the depth of cut, feed, and surface finish desired.

	Standard Malleable	*Pearlitic Malleable*
1. Carbon steel (with lubricant)	50–100 ft. per min.	25–50 ft. per min.
2. High-speed steel (with lubricant)	80–180	50–120
3. Carbide-tipped cutters and inserts	150–450	125–400
4. Oxide tip inserts	800	800

There is some evidence that approximately 800 feet per minute may be an optimum speed for machining malleable irons with presently available inserts.

MACHINABILITY OF METALS

Machinability is a term indicating the relative efficiency with which a metal is worked upon with cutting tools. It is a measure of the ease and success of operations such as turning, drilling, milling, broaching, threading, reaming, or sawing one metal in comparison with others. Machinability depends upon the depth of cut and the feed in thousandths of an inch for each passage of the tool, the speed in surface feet per minute, the desired tool life, which is the period between grinding or replacement, conformity of the product to specified size tolerances, and the degree to which the product meets surface finish requirements.

The number of parts that can be machined per tool grind is regarded as a sound measure of efficiency in machining. Factors which affect this measure are these:

1. The material being cut—its composition, microstructure, shape and size, heat-treatment, and properties.

2. The tool doing the cutting—its chemical composition and heat-treatment, the shape or contour of its cutting edge, and its lip and clearance angles.

3. The cut being made—its depth per pass, its size and shape, the speed at which it is made, and the pressure of the resulting chip or shaving on the cutting surface of the tool.

4. The machine tool on which the cutting is done—its mechanical condition, pulling power, speed and feed changes, together with the rigidity of the tool and the work-holding device.

5. The cutting fluid used—its characteristics and cooling properties.

6. The nature and cleanliness of the surface and *immediate subsurface* being machined.

The tool life may vary considerably from one type of machine tool to another. It is always important to obtain maximum time between grindings because of the cost of grinding and resetting the tools.

The many variables in machining make it difficult to lay down hard and fast rules. The ultimate for both speed and feed is often found to be

TABLE 1. PROPER RAKES AND CLEARANCE FOR TOOL BITS[40]

The following rakes and clearances are recommended for average conditions. Special production setups may require some variations:

	Rakes and Clearances in Degrees							
	High Speed Steel Cutters				*Carbide-Tipped Cutters*			
	Back Rake	*Side Rake*	*Side Clearance*	*Front Clearance*	*Back Rake*	*Side Rake*	*Side Clearance*	*Front Clearance*
Irons								
Standard Malleable Iron	3	3	6	6	0	0–2	4–6	4–6
Pearlitic Malleable Iron	6	6	6	6	0	0–2	4–6	4–6
Cast Iron, Soft—Brinell 160-193	3	3	6	6	0	0–2	4–6	4–6
Cast Iron, Medium—Brinell 193-220	2–3	2–3	6	6	0	0–2	4–6	4–6
Cast Iron, Hard—Brinell 220-240	2	2	6	6	0	0–2	4–6	4–6
Steels								
Screw Stock, SAE 1112, 1118 AISI B1112, C1118	15	20	6	6	0	3	6	6
Plain Carbon, SAE 1020, 1035 AISI C1020, C1035	15	15	6	6	0	3	6	6
High Carbon, SAE 1095 AISI C1095	5	10	6	6	0	3	6	6
Nickel Alloy, SAE 2317, 2330 AISI A2317, A2330	15	15	6	6	0	3	6	6
Nickel Chromium, SAE 3140, 3240, AISI A3140, A3240	8–10	12	6	6	0	3	6	6
Chrome Molybdenum, SAE 4140, AISI 4140	10	12	6	6	0	3	6	6
Nickel Molybdenum, SAE 4615, AISI A4615	15	15	6	6	0	3	6	6
Chrome Vanadium, SAE 6150, AISI E6150	8	12	6	6	0	3	6	6
Nonferrous								
Aluminum	8	18	6	6	25	15	8–10	8–10
Brass	2	2	6	6	0	4	6	6
Bronze	6	5	6	6	0	4	6	6
Copper	10	25	6	6	4	20	8–10	8–10

NOTE: For carbide-tipped tools, keep back rake angle as small as possible for greatest strength. Use negative rakes for older machines. In most malleable iron machining, negative back rakes as great as 7 to 10 degrees are often used. Such practice is essential when both carbide and oxide inserts are employed.

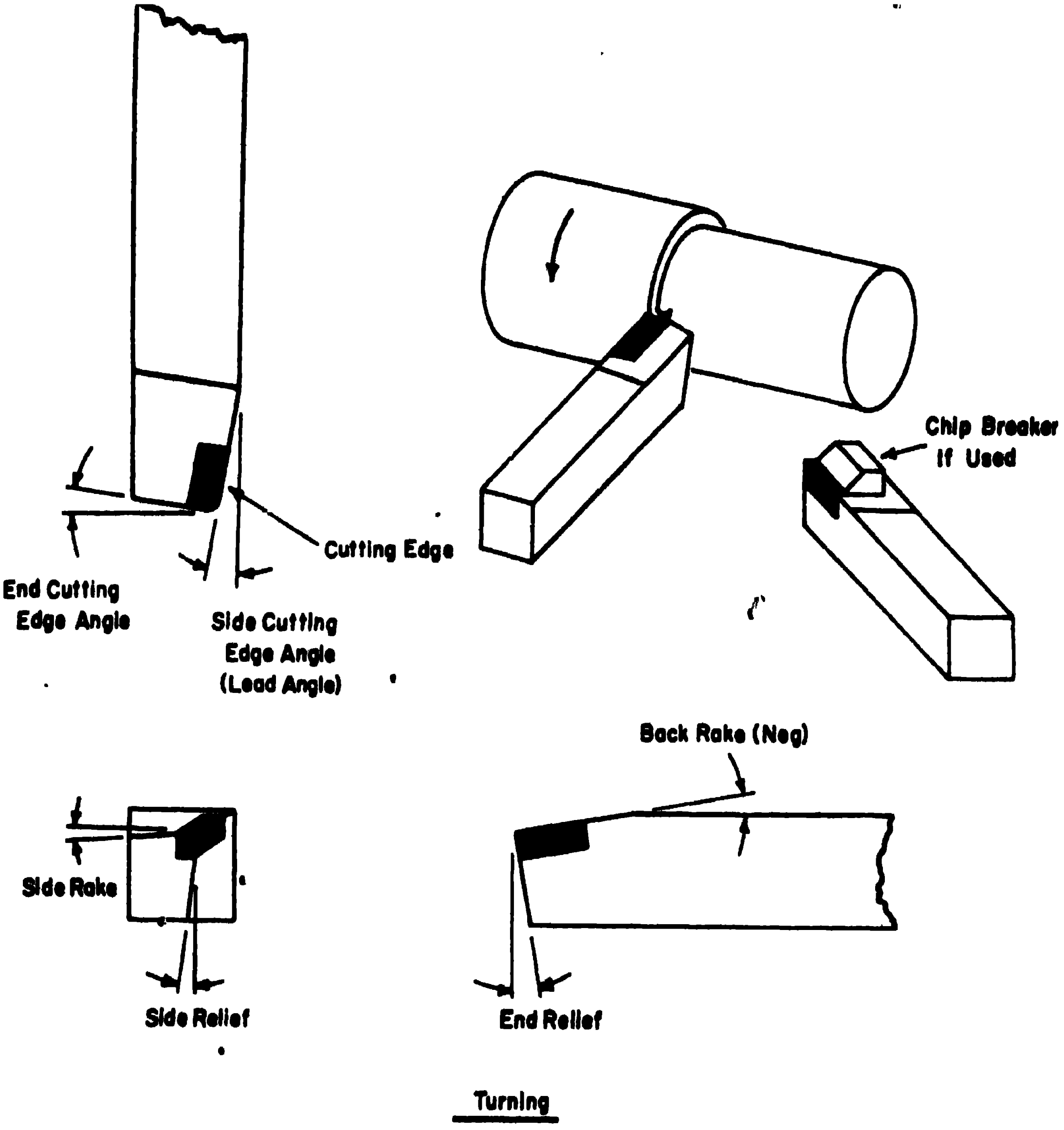


Fig. 1. Rakes, cutting edge angles, reliefs and clearances are shown as employed in this chapter. Most important are rake and side cutting edge angles, which determine resultant rake and inclination, and control tool forces and chip flow. The same general principles of tool design and critical angles apply to operations of boring, shaping, planing and some aspects of milling.

above the recommended range. This results in some cases from what might be called "critical points" arising from such causes as backlash, badly worn ways, or machine construction so light as to permit injurious periods of vibration at various combinations of speeds and feeds within normal working ranges. The operator of experience knows that some machines will labor, or "chatter," at a certain speed or feed, but will operate easily at higher rates when this critical point has been passed. Experience has shown that increasing the speeds, especially with carbide and oxide-tipped tools, may result in smoother operation. Sometimes, how-

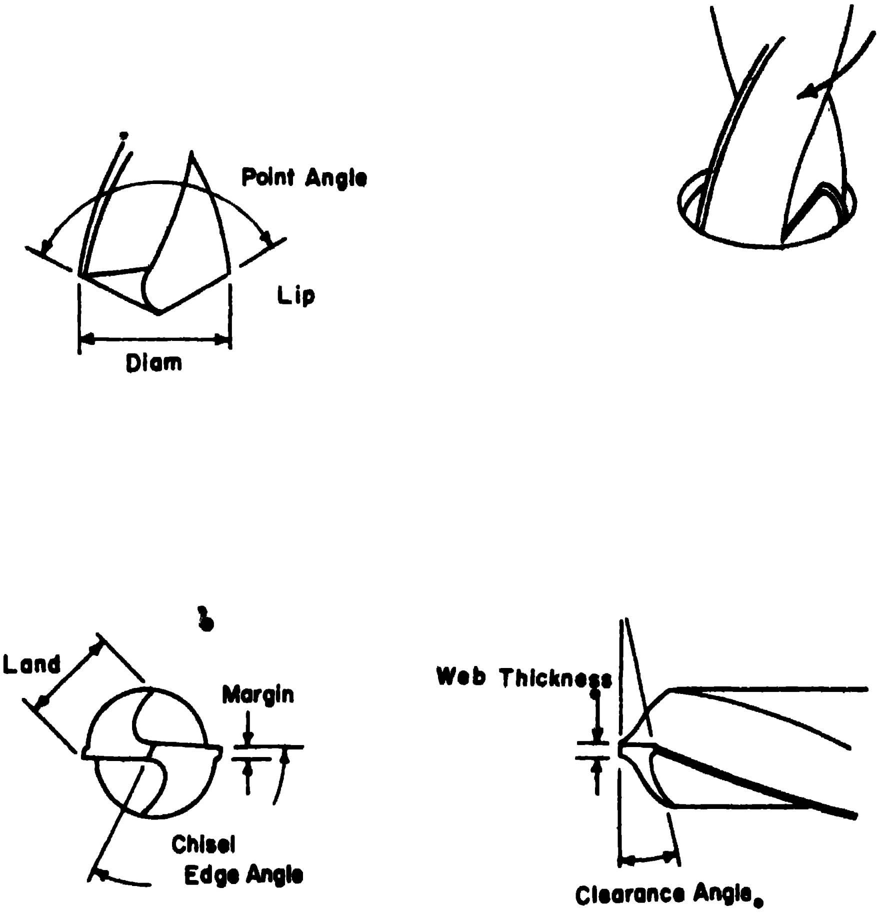


Fig. 2. **A specialized form of turning. Tool or work may rotate (as in a lathe). Drills often have multiple flutes but two is conventional as illustrated. In modern practice there are many variations in point design.**

ever, the reverse has proved to be the optimum procedure. In machining with oxide tools, moreover, it has been found in general that heavier and more rigid machine beds, spindle housings and bearings, and tool supports are required for best results.

In addition, the cutting lubricant used and the angle of contact between the cutting tool and the workpiece also affect machinability. Recommended rake angles for grinding single-point tools are shown in Table 1. The back rake angle, which largely determines resultant rake and consequently the friction between the tool and the chip, is of pronounced importance in the machining of both standard and pearlitic malleable iron and is usually negative, for malleable iron. Figures 1, 2, and 3 apply to standard machining operations such as turning, boring, shaping, planing, drilling, and milling, and define the terms

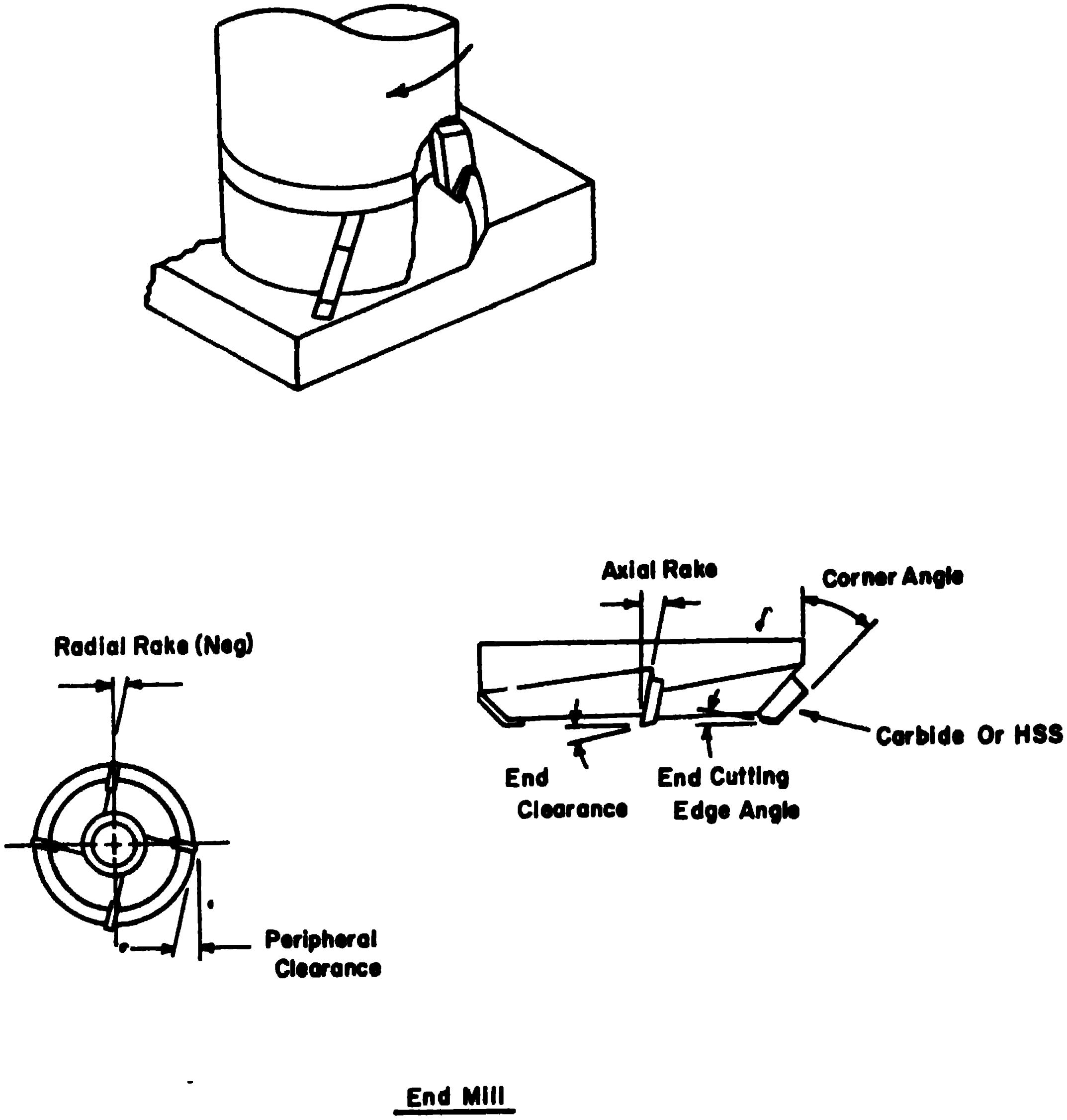


Fig. 3. This involves components of translation and rotation. Individual tooth design is similar to a planer in terms of critical angles and dimensions. The sketch primarily relates to a finishing cutter and may apply both to high speed steel and insert carbide and oxide tools.

used in the remainder of this chapter. Figure 1 is drawn to illustrate the modern use of carbide tips and carbide or oxide inserts. Figures 2 and 3, however, indicate accepted practice with high-speed steel (HSS), which is still commonly in use by most industries. In modified form, Fig. 3, which illustrates the use of inserts, may also be applied to both carbide and oxide tooling. It can be seen that in general basic terms, all machining operations are much the same, differing chiefly in the means of holding the cutting surface with relation to the material being cut and in the choice of cutting angles.

CUTTING CHARACTERISTICS

Because of the complex nature of the property termed "machinability" a comparative scale based on an arbitrary standard has been devised and is widely used. AISI B1112 cold-rolled or cold-drawn steel is the standard and is rated 100 per cent. This analysis is frequently referred to as "Bessemer screw stock" and contains a higher sulfur content than most steels. This high sulfur content is generally considered to be the cause of its ease of machining compared to most other steels. A cutting speed of 180 feet per minute, normal cutting conditions, and a suitable cutting fluid are also specified as part of the standard reference conditions.[40,128] The speed at which other materials can be machined under optimum conditions is then related to that for B1112 and is expressed as a per cent. Machinability ratings based on this procedure have been widely published[17,126,127,128,129,130,131] and used extensively for selecting materials, estimating machining costs, and setting up machining conditions in the shop.

Ferritic malleable iron is rated on the above basis at 100 to 250 per

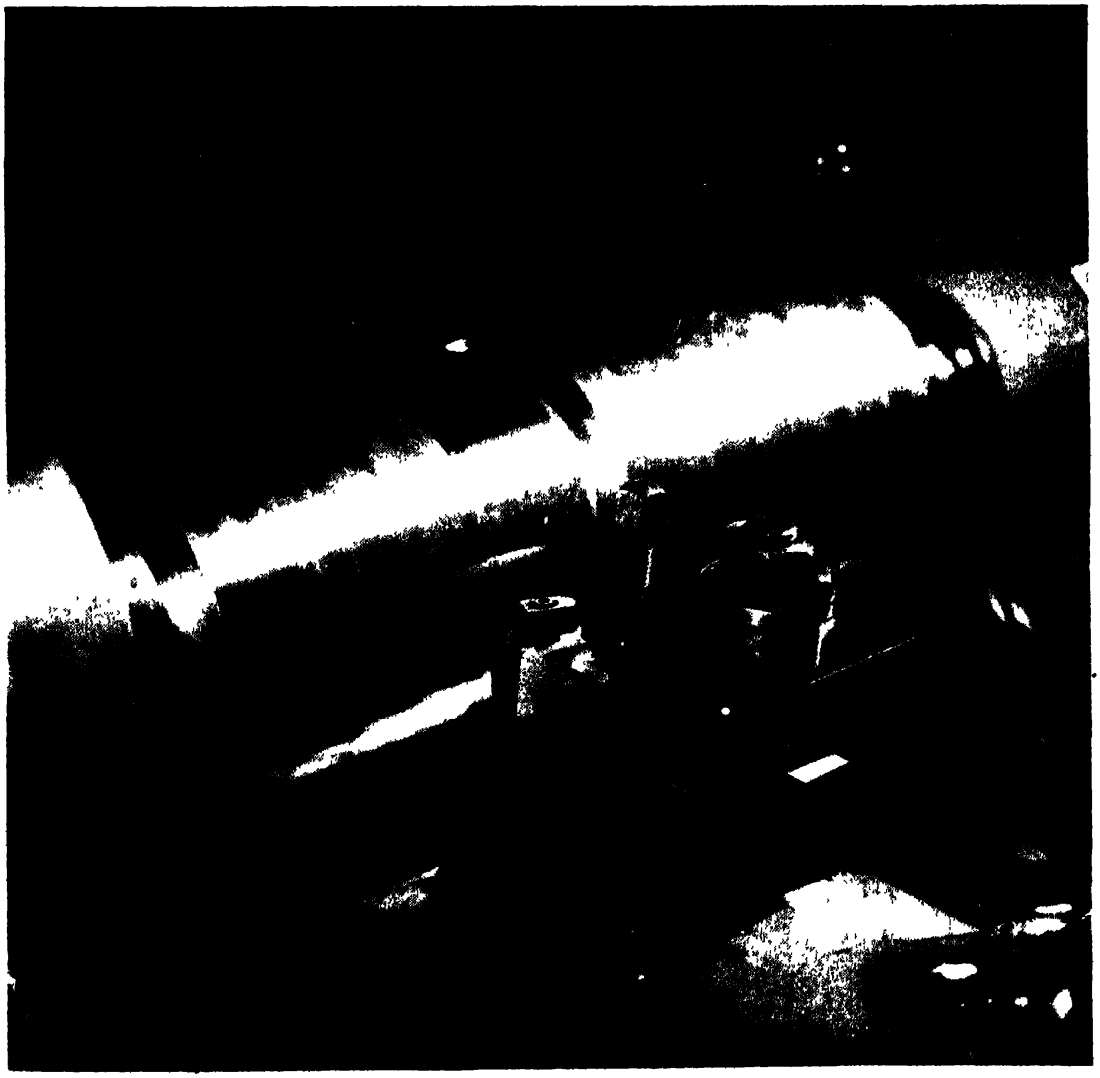


Fig. 4. **Turning of malleable iron using oxide tool. Extremely high speeds can be employed successfully.**

cent of B1112[127,128] by some investigators and 120 per cent by others.[40,126] This indicates that malleable iron is considerably more machinable than one of the most free-machining steels. This superiority of malleable iron has been attributed to the graphite nodules, which permit the chip to be easily broken and lubricate the tool, thus reducing friction.

Pearlitic malleable iron in the range of 190 to 240 Brinell has been rated at 70 per cent by some authors[129,128] while another source[126] gives 90 per cent as the rating for pearlitic malleable in the range of 180 to 200 Brinell. These ratings are higher than those for plain carbon steels of comparable combined carbon content and hardness. As in the case of ferritic malleable iron, the presence of free graphite in the structure is considered to account for pearlitic malleable's superiority.

Table 2[40,127] is a list showing the relative machinability of ferritic and pearlitic malleable irons compared to some typical steels and several other ferrous metals. This table is intended as a guide for relating malleable irons to other materials. More complete data are available for steels[181] and steels versus non-ferrous alloys.[128]

Machinability ratings[4,26] are arranged in the table below in three classes or groups: for metals having a rating over 70%, between 70% and 50%, and below 50%. The percentage values given express relative machinability, the higher values indicating the more easily machined materials. This grouping simplifies the use of Table 12 (recommendations for applying cutting fluids to various machining processes[127]).

It should be noted that comparisons are for bar steels only. Since the data in this table were obtained, minor modifications may have been made in some of the analyses specified for certain A.I.S.I. steels. Such modifications probably will not affect the machinability rating significantly, but suitable caution should be exercised in using the table.

MACHINING OPERATIONS

One view of machining operations classifies them as either rotary or reciprocating. In the first group are the major classes of turning, drilling, and milling; in the second, planing, shaping, broaching, and slotting. Grinding, sawing, and punching may also be considered as machining.

A wide range of modern operations employing carbide and oxide tools is feasible without the use of lubricants. This is true generally for ferritic structures; it is true for pearlitic irons when the structural properties are favorable and with proper choice of feeds and speeds.

TABLE 2. MACHINABILITY RATINGS OF AISI STEELS AND VARIOUS FERROUS METALS[127]

Material	*Machinability Rating (%)**	*Brinell Hardness Number*
Class I		
Standard Malleable Iron	120	110–145
Pearlitic Malleable Iron	90	180–200
Pearlitic Malleable Iron	80	200–240
Cast Iron–Soft	80	160–193
Cast Steel (0.35% Carbon)	70	170–212
Stainless Iron (12% Cr.)	70	163–207
A.I.S.I. B1112	100	179–229
Class II		
Cast Iron–Medium	65	193–220
Cast Iron–Hard	50	220–240
Wrought Iron	50	101–131
A.I.S.I. C1020	65	137–174
A.I.S.I. C1030	65	170–212
Ingot Iron	50	101–131
Class III		
A.I.S.I. C1010	50	131–170
A.I.S.I. C1070 x	45	183–241
A.I.S.I. B1340 x	45	179–235
A.I.S.I. B2340 x	45	179–235

(x) denotes a steel in mill-annealed condition.

*** Exact to the nearest 5%, based on a 100% rating for A.I.S.I. B1112 Bessemer screw stock, cold-drawn, when turned with suitable cutting fluid at 180 fpm under normal conditions using high speed steel tools.**

TURNING

Turning is any machining operation in which the work turns and the tool remains stationary. Engine lathes[127,132] are the basic machine tools employed in turning metals; they are the most versatile machine tool in many machine shops. The work is held in a collet or chuck or supported between two supports called centers. As the work is rotated, metal is removed. Turret lathes are equipped with a rotating multiple tool holder called a turret. The rotating turret permits each tool to be brought into machining position without changing the position of the work.

Most types of tools are common to the various types of turning operations. High-speed steel, brazed carbide inserts, "throw-away" carbide and oxide (ceramic) inserts are all used. High production rates with ferrous materials such as malleable iron frequently justify the use of "throw-away" carbide or oxide inserts. Figure 5 illustrates basic tool geometry and defines the angles and terminology of tool design for turning. Where lower rates of production are encountered and a wide variety of machining operations is performed on the same machine, high-speed steel tools are often used, and the individual machinist grinds his own tools to the desired geometry.

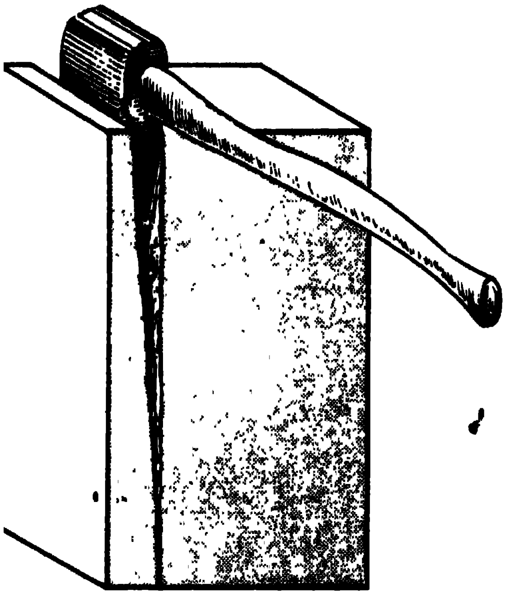


Fig. 5a. Diagram of hatchet splitting a log. This simile is often used incorrectly to illustrate the action of a metal cutting tool. Latest accepted theory does not substantiate the use of this illustration.

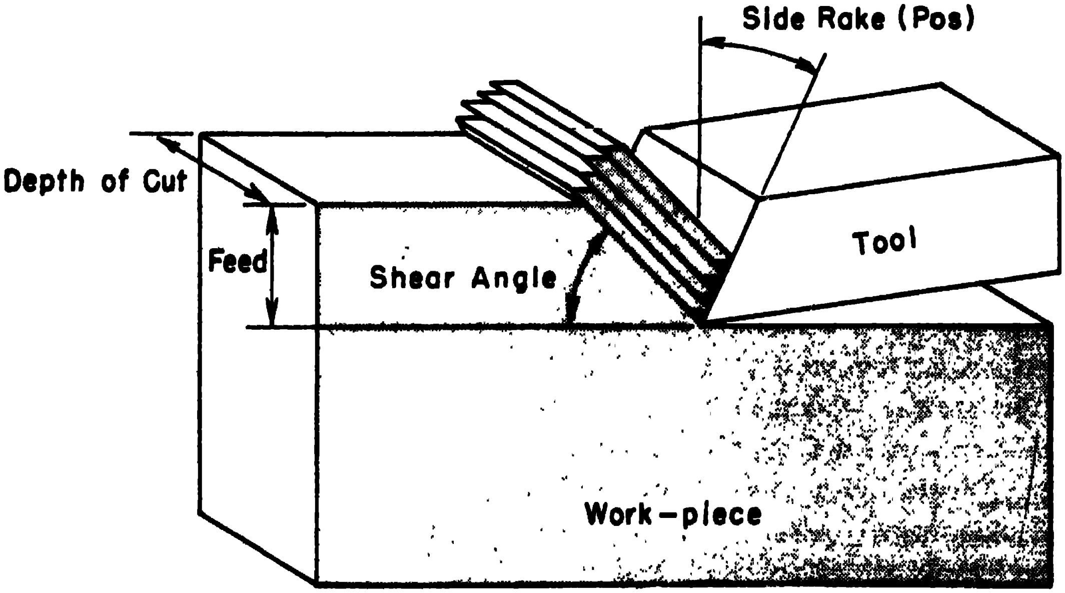
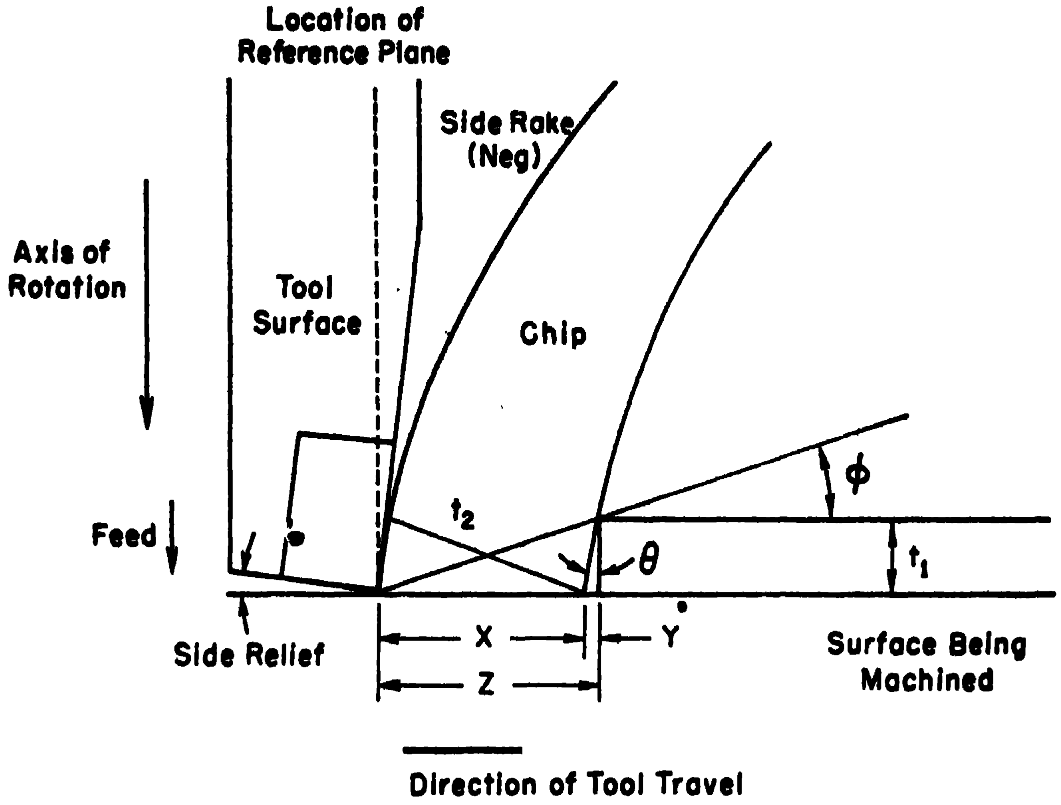


Fig. 5b. A schematic presentation of chip formation.



$$Y = t\tan\theta \qquad X = \frac{t_2}{\cos\theta}$$

$$Z = \frac{t_2}{\cos\theta} + t_1\tan\theta$$

$$\tan\phi = \frac{t_1}{Z} = \frac{t_1}{\dfrac{t_2}{\cos\theta} + \dfrac{t_1\sin\theta}{\cos\theta}}$$

$$\tan\phi = \frac{t_1\cos\theta}{t_2 + t_1\sin\theta}$$

$$\tan\phi = \frac{\dfrac{t_1}{t_2}\cdot\cos\theta}{1 + \dfrac{t_1}{t_2}\sin\theta}$$

$$\tan\phi = \frac{r_c\cos\theta}{1 + r_c\sin\theta}$$

t_1 = Thickness of Metal Being Removed (Feed Increment)

t_2 = Chip Thickness After Removal

ϕ = Shear Angle

θ = Resultant Rake (Angle Between the Tangent to the Chip as it Shears and the Reference Plane which is Normal to the Surface Being Machined)

Fig. 5c. Illustration of basic tool geometry and definition of angles and terminology of tool design for turning.

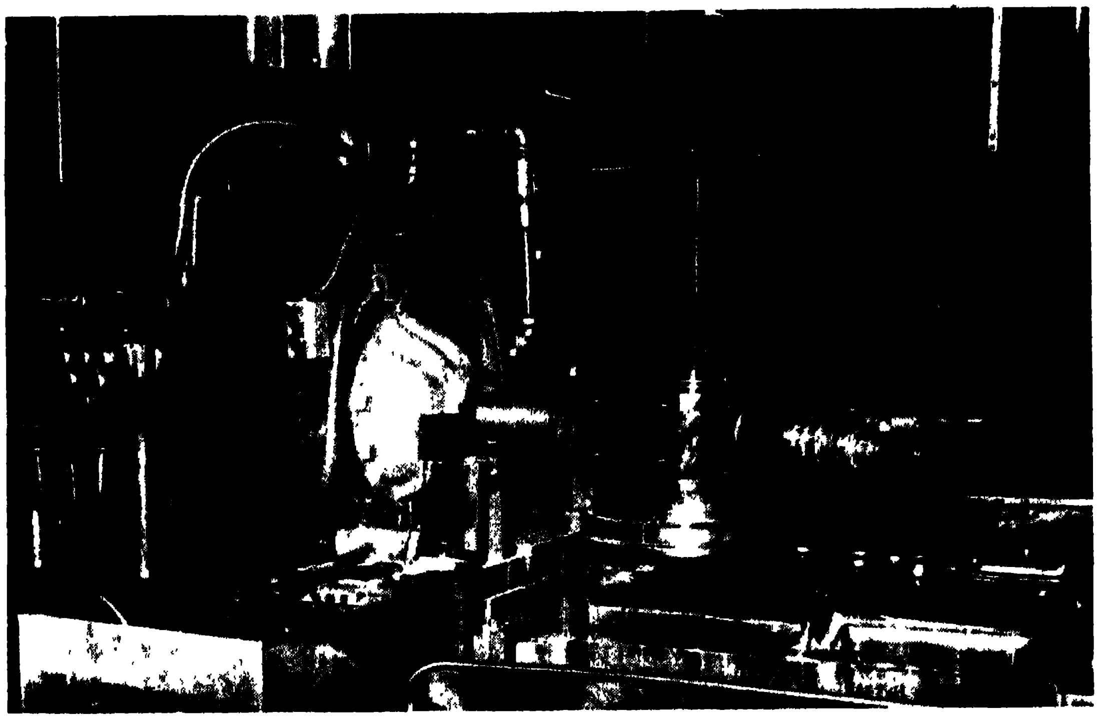


Fig. 6. A typical set-up of a multiple turning operation in a horizontal, single spindle, five-station automatic chucking machine.

Depth of cut may vary from approximately 0.100-inch to 0.125-inch or more in rough cuts and 0.005 to 0.015-inch in finish cuts. Typical feed rates vary from 0.020-inch per revolution for rough cuts to 0.004-inch for finish cuts. Machining speeds for carbide tools frequently fall in the range of 300 to 500 surface feet per minute. Oxide tools have been used at speeds of 700 to over 1,000 surface feet per minute. These speeds may vary widely depending on the material being machined, its structure and hardness, the available equipment, and the geometry of the part.

Figure 6 illustrates a typical setup of a multiple turning operation in a horizontal, single-spindle, five-station automatic chucking machine. Full details of this operation are included in the section on Typical Machining Operations. Tables 1 and 3 present data on typical feeds, speeds, and tool angles for high-speed steels and cemented carbide tools. Values given are to be taken as representative and do not cover special applications or unusual situations.

Drilling

In many of its aspects drilling may be regarded as a special case of turning. Either the drill or the piece being worked may be rotated. The latter alternative is sometimes convenient for rapid operation with a lathe or a screw machine. Critical angles and other elements of tool design bear analogy to those in other machining operations.

TABLE 3. RECOMMENDED FEEDS AND SPEEDS FOR TURRET AND ENGINE LATHES[40]
(All data are for continuous cutting with lubricant)

		Feed in Inches Per Revolution			
		High Speed Steel		*Cemented Carbides*	
Type of Material	*Depth of Cut in Inches*	*Up to 1/32*	*1/32 to 3/32*	*Up to 1/64*	*1/64 to 1/32*
		Surface Speed in Feet Per Minute			
Malleable Iron	1/32 to 1/8	120-160	90-120	220-500	175-350
	over 1/8 to 1/2	90-120	55-90	175-400	175-300
Pearlitic Malleable	1/32 to 1/8	110-140	80-110	200-400	150-300
	over 1/8 to 1/2	80-110	50-85	150-350	150-250
Soft Cast Iron	1/32 to 1/8	80-120	50-70	250-400	200-350
	over 1/8 to 1/2	50-65	40-55	200-350	150-350
Medium Cast Iron	1/32 to 1/8	75-115	45-60	200-400	200-350
	over 1/8 to 1/2	50-65	35-50	175-300	175-250
Hard Cast Iron	1/32 to 1/8	65-100	40-55	200-350	150-300
	over 1/8 to 1/2	40-55	30-45	150-250	150-200
Class I Steel*	1/32 to 1/8	70-175	50-120	340-690	300-625
	over 1/8 to 1/2	40-120	30-90	220-550	200-460
Class II Steel*	1/32 to 1/8	60-110	40-75	280-420	240-375
	over 1/8 to 1/2	35-70	20-55	180-330	170-275
Class III Steel*	1/32 to 1/8	35-80	25-60	170-330	150-310
	over 1/8 to 1/2	20-55	15-40	110-275	100-220

*** For definitions of these classes of metal, see Table 2.**

NOTE: For continuous cuts without lubricant, decrease speeds 25 per cent. For intermittent cuts with lubricant, decrease speeds 15 per cent. For intermittent cuts without lubricant, decrease speeds 40 per cent. For light finishing cuts and fine feeds, speeds can be increased 50 to 100 per cent.

In the drilling of malleable iron and other cast ferrous materials, feeds and speeds may cover a wide range, depending upon the physical characteristics of a material and the results the operation is desired to achieve. Speeds may vary from only a few to more than 2,000 revolutions per minute, again depending upon the prevailing conditions. Tables 4 and 5 give some typical values in common use with high-speed steel drills.

Malleable irons, particularly those with a ferritic structure, have the advantage that they can be drilled at high feeds and speeds with good drill life and without the use of a coolant or lubricant. The same is true of some pearlitic malleable irons. The deciding factors may include a combination of chemical composition, processing variables, and the resulting microstructure.

Some typical speeds and feeds commonly employed in production drilling operations are shown in the accompanying Tables 4, 5, 6 and 7. These figures may be conveniently used in planning operations.

As compiled, these tables are merely representative of practice with high speed steel twist drills and standard conical points. They are published as guides and are not intended to cover unusual situations or some of the most recent methods employing new lubricating and cooling techniques, or special point contours.

Table 4. Cutting Speeds For Drilling Various Materials[40]

Material Being Machined	*Cutting Speed in Feet per Minute with High Speed Steel Drills*
Standard Malleable Iron	70-90
Pearlitic Malleable Iron—Brinell 180-200	60-80
Pearlitic Malleable Iron—Brinell 200-240	50-70
Cast Iron, Soft—Brinell 160-193	80-100
Cast Iron, Medium—Brinell 193-220	70-90
Cast Iron, Hard—Brinell 220-240	60-80
Steel—Class I —See Table 2	90-110
Steel—Class II —See Table 2	80-100
Steel—Class III—See Table 2	60-80
Steel Castings—to 0.20 per cent carbon	70-80
Steel Castings—high carbon, annealed	65-75
Steel Castings—3½ per cent nickel—0.30 per cent carbon annealed	60-70
Drop Forgings, 0.15 to 0.25 per cent carbon	60-70
Drop Forgings, high carbon, annealed	50-60
Drop Forgings, alloy	50-60
Stainless Steel—Type 410	50-60
Tool Steel, annealed	50-60
Brass, soft yellow	200-275
Bronze (Tobin-Everdur, etc.)	90-110
Bronze (Manganese Bronze, Vanadium Bronze)	55-75
Aluminum	600-900

Table 5. Recommended Drilling Feeds as a Function of Drill Size for Pearlitic Malleable Iron*[206]

Diameter of Drill—Inches	*Feed in Inches per Revolution*
1/16–1/8	.002–.004
1/8–1/4	.004–.006
1/4–3/8	.006–.008
3/8–1/2	.008–.010
1/2–3/4	.010–.013
3/4–1	.013–.017
1" and over	.017–.022

*** Cutting speed—70-105 surface feet per minute.**

EXAMPLE: Drilling through 5/16" of metal—6 holes per part—11/32" diameter drill.
Speed—1150 rpm—103 surface feet per minute.
Feed—.006" per revolution.
Tool Life—Approximately 3300 holes per grind.
Coolant—20:1 ratio of soluble oil.

Table 6. Feeds For Drilling Various Materials, Using High Speed Steel Drills

Minimum feeds for two-lip drills in inches per revolution. For core drills, add one-half of the given feed for each additional lip. The feeds for the various metals are about the same for very small drills; for the large diameters the general relationships are that malleable iron may be fed about 25 per cent heavier than steel and 20 per cent less than cast iron.

Drill Diam., Inches:	1/16	3/32	1/8	5/32	3/16	7/32	1/4	9/32
	Feeds per Revolution in Inches							
Malleable Iron	.003	.0035	.0045	.005	.0058	.0065	.0075	.008
Cast Iron	.003	.0035	.0045	.005	.006	.007	.008	.009
Steel	.003	.0035	.004	.0045	.005	.0055	.006	.0065

Drill Diam., Inches:	5/16	11/32	3/8	13/32	7/16	15/32	1/2	9/16
	Feeds per Revolution in Inches							
Malleable Iron	.009	.0095	.010	.0105	.011	.012	.0125	.013
Cast Iron	.009	.010	.011	.011	.012	.013	.013	.014
Steel	.007	.0075	.008	.0085	.009	.0095	.010	.0105

Drill Diam., Inches:	5/8	11/16	3/4	13/16	7/8	15/16	1	1 1/8
	Feeds per Revolution in Inches							
Malleable Iron	.014	.0145	.015	.016	.016	.017	.0175	.019
Cast Iron	.015	.015	.016	.017	.017	.018	.019	.020
Steel	.011	.0115	.012	.0125	.013	.0135	.014	.015

Drill Diam., Inches:	1 1/4	1 3/8	1 1/2	1 5/8	1 3/4	1 7/8	2
	Feeds per Revolution in Inches						
Malleable Iron	.020	.020	.020	.020	.020	.020	.020
Cast Iron	.021	.021	.021	.021	.021	.021	.021
Steel	.016	.016	.016	.016	.016	.016	.016

Deep Hole Drilling

The rate of feeding drills is regulated entirely by the diameter of the drill. For example, for a one-eighth-inch drill a feed of .004-inch per revolution is proportionately correct, but when a three-eighths-inch diameter drill is used, it is possible to push this drill much faster to a feed of from .008-inch to .010-inch. This is because of the relatively greater strength of the larger drill. As the holes being drilled become deeper in relation to the diameter of the drill, the operation becomes more difficult. In some difficult ones it is possible to use a so-called "oil hole" drill which has an oil passage, feeding lubricant directly to the cutting edge, regardless of chips in the hole. Through the use of these it is possible to extend the length of the cut four to five times the diameter of the drill. Oil hole drills are not usually available in the smaller sizes, and are confined to as few jobs as possible, because of their cost. The five-eighths-inch size is generally the smallest available. They are commonly used on automatic screw machines. Drilling generally employs a surface cutting speed lower than one used for turning. It is good practice to reduce both the speed and feed when drilling holes with a depth several times the diameter of the drill, because of:

1. Clogging of chips in the drill flutes,
2. Inability of the coolant to reach the cutting lips through the clogged flutes.

It is desirable to back the drill out at regular intervals in deep hole drilling, to help clear the chips. There is no hard and fast rule for this, since the depth of the hole in relation to its diameter, the amount of chips to be cleared, and the number of cutting lips all influence the amount of coolant reaching the cutting lips. A rough rule of thumb is to back the drill out once for each drill diameter of depth.

TABLE 7. DEEP HOLE DRILLING

Speed and Feed Reduction for Deep Hole Drilling. (This is general and not to be used literally for small-diameter drills.)

	Reduction Below Standard Drilling in Per Cent	
Depth of Hole	*Speed*	*Feed*
3 times drill diameter	10	10
4 times drill diameter	20	10
5 times drill diameter	30	20
6 to 8 times drill diameter	40	20

REAMING OR FINISH BORING

After holes have been drilled or bored, finishing to close tolerances can be done by either a reaming or a finish-boring operation. It should be kept in mind that a reamer is a balanced tool, in that it cuts on both sides. Also cutting edges which are adjustable to balance and size may be inserted on a boring bar to accomplish the same result as reaming. This boring tool may offer the advantage of quickly finishing the piece with the size tolerances and surface condition required, at high speed and relatively heavy feed, since the balanced effect of the cutting edges tends to avoid inaccuracies that might result from spring in the boring bar or tool holder. They are commonly used on horizontal boring machines. Another method of finishing holes to close tolerances is to use carbide-tipped tools with either single or multiple cutting edges, employing very light feeds but very high speeds to do the job quickly. Holes may be finished to close tolerances by grinding or honing after drilling or rough boring. This method is more applicable to finishing holes in steel which has been hardened after the drilling or rough boring. Hardening heat-treatment may cause distortions and also may injure finished surfaces; grinding or honing frequently offers the best method of making the corrections.

Recommended feeds and speeds for reaming are not presented in the tables that follow, since they may be determined directly from the various tables ot recommended drilling practice. In general, speeds in reaming should be two-thirds to three-fourths the speed listed for drills of similar size. Choice should be on the lower side, since a reamer can be quickly ruined by speeds only slightly too high. Feeds in reaming should be two to three times the feed listed for drills of the same diameter. A coarse feed will tend to produce revolution marks and rough walls. Too fine a feed makes the reamer idle in the cut and subjects it to undue wear in proportion to the amount of work produced.

TAPPING

Most taps are broken by insufficient speed. It is highly important that the tap be given enough momentum to carry it through the difficult job it has to do.

Taps should be operated at the highest speed permitted by equipment, lubrication, and type of work, for high speed not only increases production, but gives longer tap life and more accurate threads. A good practical rule for the speed of taps is to run them at the same speed as the tap drill. The tap will, however, often give excellent results at still higher speeds. In general, the speed recommended for taps may be resolved into the following, with the first figure shown as the safe starting speed and the second figure the possible, but not necessarily the maximum, speed obtainable:

Material	*Feet per Minute*
Malleable and cast iron	90 to 150
Low carbon steels	80 to 100
High carbon steels	40 to 75
Alloy and stainless steels	40 to 75
Free-cutting yellow brass	150 to 250
Leaded commercial bronzes	150 to 250
Extruded architectural bronzes	150 to 250
Yellow or red brass	60 to 150
Naval brass	60 to 150
Tobin bronzes	60 to 150
Leaded phosphorus bronzes	60 to 150
Everdur	60 to 150
Manganese bronzes	60 to 150
Phosphorus bronzes	30 to 60
Nickel silver	30 to 60

MILLING

Milling machines are versatile and precision machine tools capable of high metal removal rates.[127,132] They are used to produce finished surfaces, ranging from flat to very irregular contours, and are adaptable to specialties such as generation of cam profiles. Drilling and boring may also be done on a milling machine.

To remove metal by milling, a rotating multiple cutting edge cutting tool (Fig. 3) is fed into the material in a direction perpendicular to the axis of rotation. Actually, the cutter only rotates, and the part moves relative to it. The cutting action and chip formation are discontinuous, with each cutting edge in contact only part of each revolution. Milling cutters are available in a wide variety of standard sizes and forms[182] in high-speed steel, cast alloy, carbide, or oxide. The tool cutting edge nomenclature is applied to milling cutters just as to other cutting tools (Fig. 3). Different values of these parameters are used for different materials and types of cuts.

The depth and face of cut usually control the selection of the type and size of cutter, and in most cases the selection is correct. When the feed or chip per tooth is also correct, it generally follows that favorable production is being secured for any given cutter run at the right speed.

The average operator instinctively checks the cutter's surface speed and sets some travel feed, but does not always check the feed per tooth. This is apparently due to the fact that milling cutters have multiple rather than single cutting edges, and that it is somewhat difficult to calculate the feed per tooth. The formula on page 486 presents a simple way of determining this feed.

A cutting speed should be used which is as high as possible commensurate with satisfactory life of the tool between grinds. A guide to determine the proper speed will be found in Table 8.

In arriving at the proper feed to use on a given milling cutter for various materials, Table 9 should be consulted, and it should be borne in mind that, for malleable iron, it is good practice to lean toward the higher feeds per tooth.

Before a milling job is started, the cutter has to be selected. Then the surface cutting speed is set for that particular cutter and the material to be machined. On page 486 in the Appendix the cutting speed is translated into the R.P.M. of the cutter shaft or spindle. Recommended feeds and speeds are given in Tables 8 and 9.

The three types of cut listed in Table 9 may be defined as follows:

Rough cuts are the initial cuts made for the purpose of removing material but not for sizing. A rough cut alone may be sufficient for clearance purposes. Coarse finishing cuts are secondary cuts made for the purpose of obtaining a level surface when roughness or coarseness to touch is not objectionable. Coarse finishing cuts are to be desired when the part is subsequently ground, since the grinding wheel will "bite in" on a coarse surface much better than on a smooth surface. This is true of other types of machine work as well as milled surfaces.

Finishing cuts are used when the quality of smoothness to touch as well as a level surface is desired. In general, finishing cuts are used when a rubbing motion will occur between the parts in the final assembly.

TABLE 8. CUTTING SPEEDS FOR MILLING VARIOUS MATERIALS[40]

Material Being Machined	*Cutting Speed (f.p.m.) With High Speed Steel Cutters*	
	Rough	*Finish*
Standard Malleable Iron	70–80	100–120
Pearlitic Malleable Iron—Brinell 180-200	60–75	90–100
Pearlitic Malleable Iron—Brinell 200-240	55–65	80–90
Cast Iron, Soft—Brinell 160-193	70–80	100–120
Cast Iron, Medium—Brinell 193-220	60–75	90–100
Cast Iron, Hard—Brinell 220-240	55–65	80–90
Steel—Class I —See Table 2	90–100	100–120
Steel—Class II —See Table 2	80–90	90–100
Steel—Class III—See Table 2	60–70	70–80
Steel Castings—to 0.20 per cent carbon	50–60	60–70
Steel Castings—high carbon, annealed	40–50	50–65
Steel Castings—3½ per cent nickel—0.30 per cent carbon, annealed	40–50	50–60
Drop Forgings, 0.15 to 0.25 per cent carbon	45–55	55–65
Drop Forgings, high carbon, annealed	50–60	60–70
Drop Forgings, alloy	50–60	60–70
Stainless Steel—Type 410	50–60	60–70
Tool Steel well annealed	50–60	60–70
Brass, soft yellow	200–250	300–500
Bronze (Tobin-Everdur, etc.)	80–100	150–200
Bronze (Manganese Bronze, Vanadium Bronze)	40–60	80–100
Aluminum	600–800	800–1000

TABLE 9. FEEDS FOR MILLING[40]

Using High-Speed Steel Cutters

Nature of Cut and Cutter	*Rough Cuts to 3/16-Inch Depth*	*Coarse Finishing Cuts to 1/16 Inch Depth*	*Finishing Cuts to 1/32 Inch Depth*
	Feed Per Tooth Per Revolution of Cutter, Inches		
Metal slitting saw with side chip clearance	.001 to .003	.001 to .003	.001 to .003
Side milling cutter	.004 to .010	.006 to .012	.002 to .004
Plain helical mill	.006 to .012	.008 to .015	.002 to .005
Form cutter	.004 to .010	.006 to .010	.002 to .004
Shell end mill—over 2 inches	.006 to .010	.006 to .012	.002 to .006
Face mill—inserted tooth	.007 to .016	.010 to .020	.004 to .008

Using Two-lipped End Mill

Cutter Diameter, Inches	¼	⅜	½	¾	1 to 2
Feed per Tooth, Inches	.0006 to .001	.001 to .0015	.0015 to .003	.002 to .004	.003 to .008

PLANING, SHAPING, AND SLOTTING[126,127]

Planers, shapers, and slotters are reciprocating machine tools in which the cutting action is obtained by a straight back-and-forth motion of the tool with respect to the workpiece, or of the workpiece with respect to the tool. They are used principally for the production of flat and angular surfaces. These machines are designed to make straight-line cuts, and the cutting tools used in both machines are identical except for size. Shapers are generally defined as those in which the cutter moves on an arm or ram, while the work is held stationary. In a planer the work is clamped to a bed which moves back and forth while the tool remains stationary. This type of machine tool is rarely employed for the products of the malleable iron industry, since its use is restricted to large castings cumbersome to handle.

The feed of a planing tool varies widely in different kinds of materials and classes of work. It is also governed by the depth of cut, the nature of the cut (whether roughing or finishing), and the rigidity of the work when clamped into position.

The speeds for planing usually vary from 30 to 50 feet per minute on the cutting stroke, with a return speed 3 to 4 times as great. A general idea of planer speeds may be obtained from the following figures:

Material	*Roughing Cut (f.p.m.)*	*Finishing Cut (f.p.m.)*
✓Steel castings	30 to 35	20
✓Wrought iron	30 to 45	20
✓Malleable iron	40 to 50	20 to 25

Feeds and speeds for shaping and slotting operations would, generally speaking, be about half of those for uninterrupted cuts under equivalent conditions.

Principles which govern the shape of turning tools also apply in the grinding of tools for planing. The amount of back rake and side rake provided depends upon the hardness of the material, and the direction of the resultant rake should be negative. The end relief should be about 4 to 8 degrees for planer tools, which usually is much less than for lathe tools. This small clearance is allowable because a planer tool is held about square with the platen, whereas a lathe tool, the height and inclination of which can be varied, may not always be clamped in the same position. These observations, tables, and illustrations apply primarily to high-speed steel tools, or brazed-tip carbide single-point tools.

GRINDING[126,127]

Three functions are basic to all grinding operations; usually one is dominant and the other two are of secondary importance:

1. *To generate size.* This means to remove enough material to bring the workpiece to within the close tolerance of size desired.

2. *To generate surface.* This means to produce a good finish or luster on the workpiece. It may or may not involve holding to close tolerances.
3. *To remove stock.* This means stock removal for its own sake, tolerances and finish being secondary if considered at all. Snagging is an example of this function.

The standard grinding wheel shapes are shown in Fig. 7, and the uses of these shapes are indicated as follows:

Wheel types Nos. 1, 5, and 7 are used for internal, cylindrical, tool, and offhand grinding, and snagging. The recesses in types Nos. 5 and 7 give clearance for mounting flanges. Type No. 1 is the kind used for cutting-off wheels, and as such does not exceed ⅛-inch in thickness and may be as thin as 0.006-inch.

Type No. 2 is used for surface-grinding on either horizontal- or vertical-spindle machines.

Type No. 4 is used principally for snagging. The tapered wheel with tapered mounting flanges is a safety device to prevent pieces of the wheel from flying out if it should break during operation.

Type No. 6 is used principally for surface grinding on either horizontal- or vertical-spindle machines. It may be obtained with a beveled instead of a straight face.

Type No. 11 finds its principal use on a tool and cutter grinder, although it may be used for snagging. It may also be obtained with a beveled face.

Type No. 12 finds its principal use on a tool and cutter grinder.

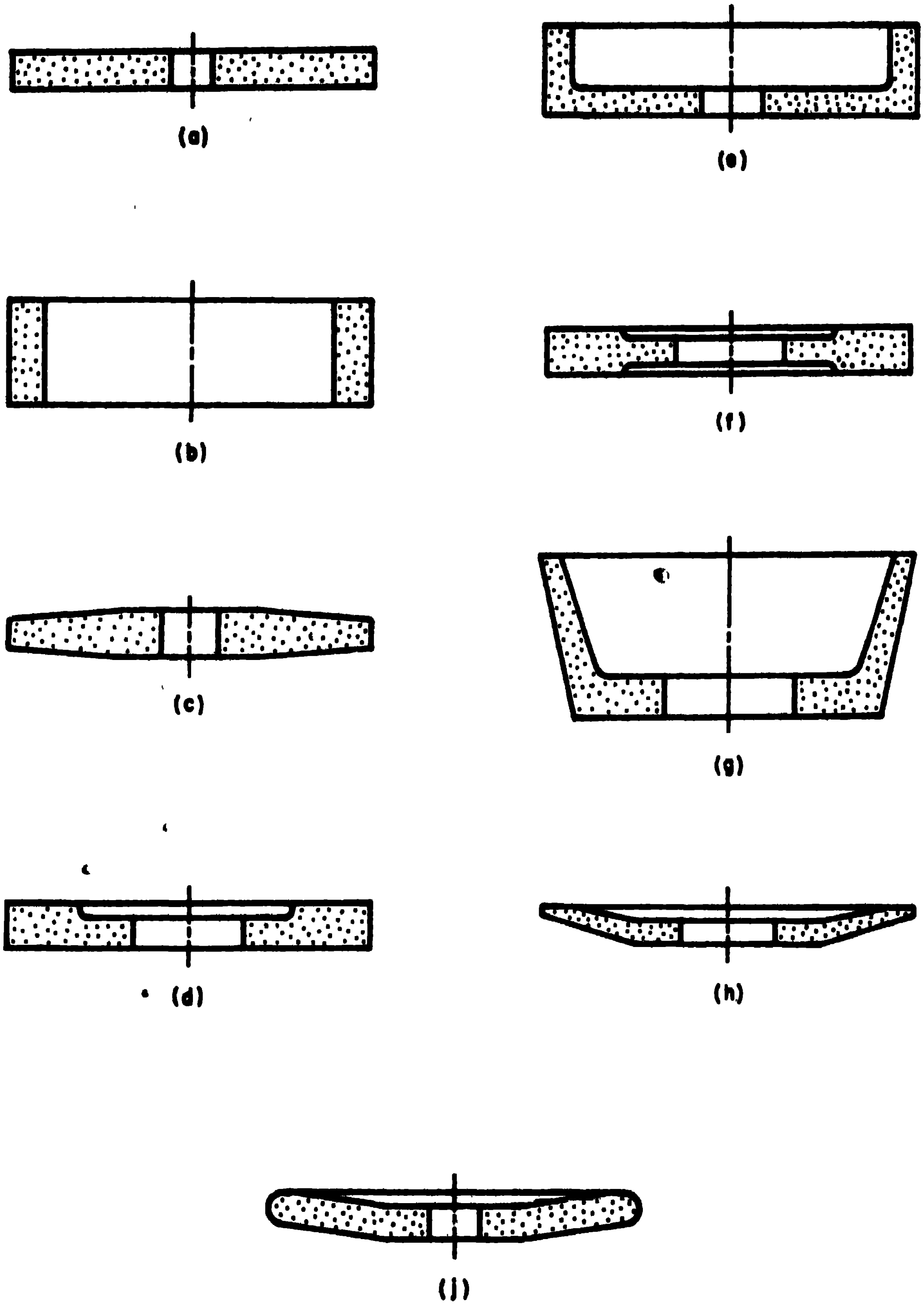
Type No. 13 finds its principal use as a "saw gummer" (sharpener).

It is very difficult to prescribe specific feeds and speeds for grinding. A few general statements, however, may be made. Grinding wheel speeds are in the range of 5,500 to 6,500 surface feet per minute (SFM) with work speeds of about 40 to 50 SFM. The extreme limits of work speed are 30 SFM for hardened steel and 100 SFM for finishing cuts on material such as malleable iron. It is generally no problem for the grinding operation directed toward generating size to hold a tolerance of ± 0.0005-inch. Closer tolerances may be had, and very fine precision work on the order of ± .0001 or ± .0002-inch is produced daily where required. Malleable iron will produce a very high luster and smooth surface as illustrated in Fig. 8.

The third function, that of removing stock, is generally associated with snagging or the removal of excess material where the gates and risers are broken from malleable castings.

PUNCHING

Punching is a type of operation for which special punches and dies



Standard grinding wheel shapes

(a) Type no.1 - Straight
(b) Type no.2 - Cylinder
(c) Type no.4 - Tapered two sides
(d) Type no.5 - Recessed one side
(e) Type no.6 - Straight cup
(f) Type no.7 - Recessed both sides
(g) Type no.11 - Flaring cup
(h) Type no.12 - Dish
(j) Type no.13 - Saucer

Fig. 7. Standard grinding wheel shapes.

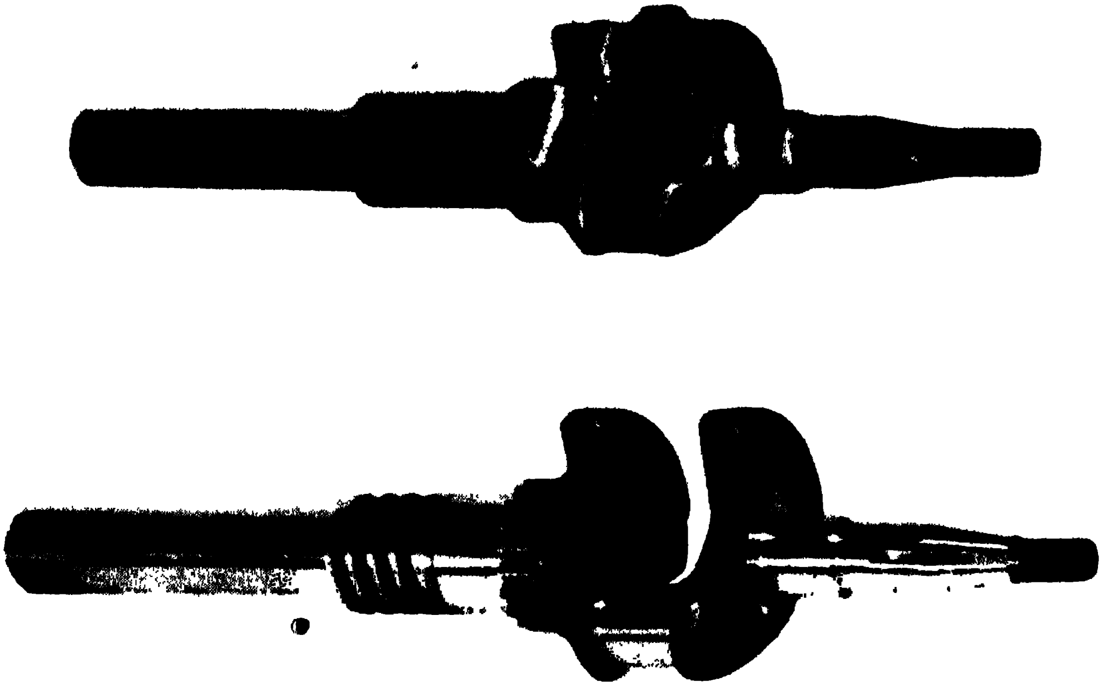


Fig. 8. **A pearlitic malleable crankshaft illustrating the high luster and smooth surface finish attainable with this material.**

must be designed to suit the individual requirements. For this reason it is best suited to long runs not requiring too frequent change of tooling. Malleable iron, particularly ferritic grades, is readily punched. Reasonable dimensional tolerances can be maintained. Hole sizes up to ½-inch diameter and section thicknesses of the order of ½-inch can be handled quite effectively. In the section on typical machining operations, Case Histories 1 and 4 give details of two such operations currently in large production.

MFS RESEARCH

In 1957 the Malleable Founders Society initiated machinability studies at Purdue University, after it was discovered, as the result of cooperative studies conducted by the Handbook Committee, that horsepower measurements alone did not yield adequate data concerning the machining of malleable iron.

Tool life studies on specimen cylinders cast from a standard pattern as well as torque and thrust drill measurements were initiated to supplement the original data.

The following general conclusions may be drawn from the data assembled to date. It should be emphasized, however, that the findings listed apply only to the specific tool geometry, speeds, feeds, and other variables investigated:

1. Optimum machining speeds of malleable iron, using carbide tools, lie between 300 and 500 SFM; using oxide tools, between 600 and 900 SFM.

2. At the speeds and feeds possible with carbide and oxide tools, the energy requirement (unit H.P.) for machining malleable iron apparently is not wholly dependent upon the hardness of the material.

3. Surface finish measured both parallel and perpendicular to the cut is substantially independent of the hardness of the material.

4. The use of oxide tools, without changing tool geometry, improved surface finish by a factor of at least two to one.

5. The energy requirement (unit H.P.) for equal rates of stock removal is considerably less for oxide tools than for other tool materials.

6. If oxide tools can be employed, both production rate and tool life increase. In one instance conversion to the oxide insert bits resulted in a 50 per cent increase in depth of cut, doubling of feed rate, approximately 100 per cent increase in production (pieces per hour) and ten-fold increase in tool life.

7. Malleable iron in all grades is inclined to form a type 1 discontinuous chip. This is considered a desirable characteristic, because the shearing and frictional forces and horsepower requirements are lower for its formation.

8. The type of tool edge (precision or utility) was found to be highly important with respect to power requirement and surface finish.

The employment of a utility edge in the first and roughing cut, particularly with carbide tools, often results in the formation of an undesirable type 3 welded and extruded secondary chip.

9. Several variables, among them microstructure, chemical composition, and processing are found to be of considerable importance in the machining of malleable iron. Apparently no single property can be employed as a basis for machinability ratings.

10. The use of a coolant or lubricating fluid at the high speeds employed in machining malleable iron with carbide or oxide tools may be of doubtful value.

11. Ferritic malleable iron can be drilled without a lubricant at speeds up to 700 r.p.m. and feeds up to 0.020-inch per revolution ($\frac{1}{2}$-inch diameter drills). The use of lubricants is found helpful with the high strength pearlitic irons at speeds up to 1,200 r.p.m. and feeds up to 0.008-inch per revolution.

METAL-CUTTING FLUIDS AND COMPOUNDS

Machining involves the removal of excess metal as chips under rather stringent conditions.[135] As the sharp edge tool moves ahead, the metal adjacent is placed under compressive stress until shear strength is exceeded and a chip is formed by a combination of shearing and deformation.[136] This process in most cases takes place in a series of discrete steps resulting in a segmented chip which curls away from the face of the tool. Pressure between tool and chip and freshly machined surface is often quite high, sometimes reaching values in excess of 100,000 psi[135,141,142,143,144,145,146] in the former case. Frictional forces may also be high, depending upon the materials of which the workpiece and tool are composed and other local conditions. This results in considerable heating at the point of contact with temperature ranging from several hundred to over 2400 degrees F.,[133,134,135,137,138,139,140] the latter values applying particularly in the case of modern high-speed machining techniques, employing carbide and oxide tools. In some cases the chip formation is almost a complete shear process, Type I chip[125,126,135,136] as is often the case with malleable irons, particularly ferritic structures. Here temperatures in the main are not excessive. With very high strength materials, however, temperatures may reach or exceed the melting point of the metal in the shear area, resulting in considerable plastic deformation before shearing, welding of the chip segments, and even the formation of nearly continuous type 2 and 3 chips.[125,126,135,136] (Figure 9.)

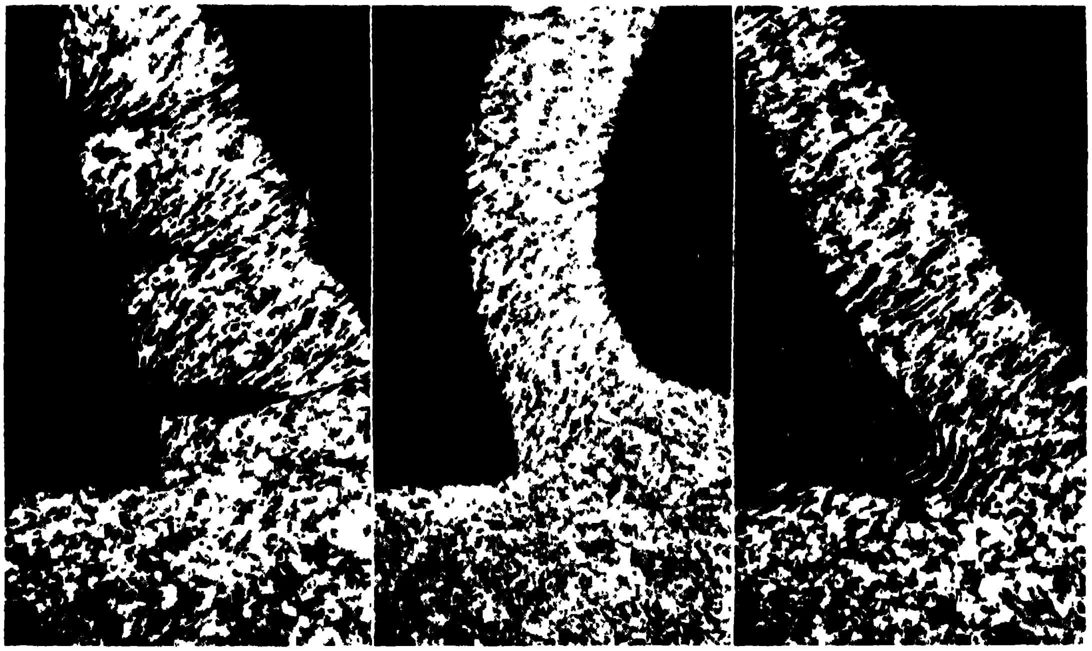


Fig. 9. **Chip size for Type I, II, and III chips. Malleable iron has a Type I chip formation. (Magnification 75 ×.)**

The use of cutting fluids has become recognized as a means of reducing temperatures at the point of contact, providing a lubrication between tool chip and workpiece and possibly in other ways reducing the severity of the conditions prevailing. The exact role of metal-cutting fluids and mechanisms involved, has recently been the subject of an extensive series of investigations. These are summarized in an evaluation report recently issued by Battelle Memorial Institute.[135] The latter is accompanied by an extensive bibliography to which the reader is referred. Here the prime functions of a cutting fluid are declared to be to reduce energy input under fixed machining conditions, to extend tool life, to allow greater depth of cut and feeds, to improve surface finish, and to allow cutting at higher speeds.

Over a period of years the use of cutting fluids has become well established through a variety of empirical techniques. As a result, three types of cutting fluids have in the main evolved. The composition and relative usage of these as given by one authority[135,147] appears in Table 10.

TABLE 10. COMPOSITION AND RELATIVE MARKETS FOR COMMERCIAL CUTTING FLUIDS[135]

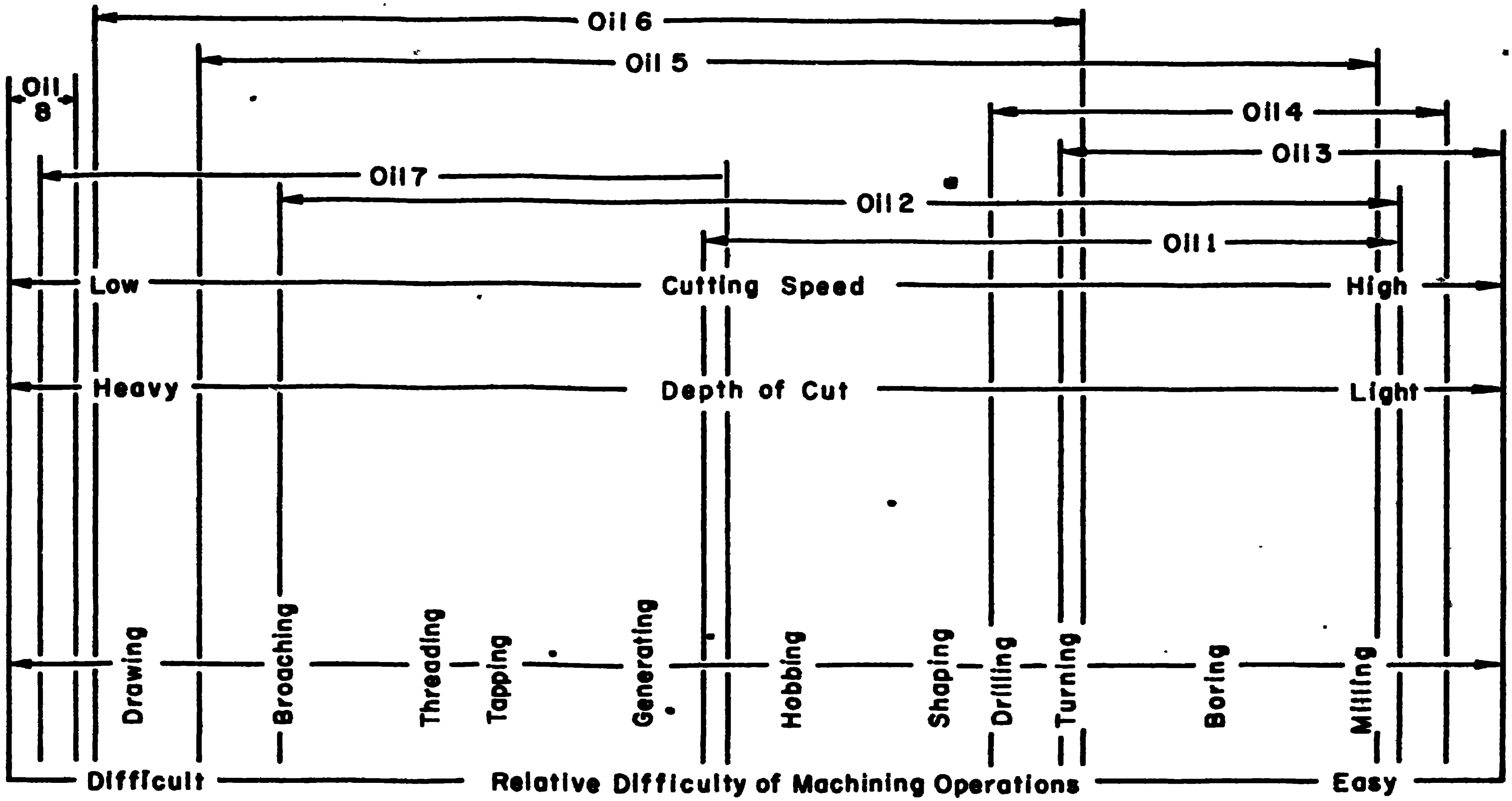
Cutting Fluid	*Composition*	*Relative Market per cent*
Straight oil		
Active	(a) Sulfur, 1 per cent dissolved at 180-250 F in mineral oil (b) Sulfur, 2-3 per cent, dissolved at 400-500 F in mineral oil (c) Sulfur, 2-3 per cent, chlorine 1 per cent, in mineral oil	60
Inactive	Fatty oil, 5-25 per cent (lard, tallow, sperm, rapeseed, coconut) Fatty acid, 1 per cent Mineral oil Sulfur in unreactive form	
Soluble oil	Mineral oil, 90 per cent Coupling agent (glycol or alcohol) Emulsifying agent Germicide, wetting agent, antifoam, water softener	35
Water Solution	Alkali, 1-2 per cent (sodium borate, carbonate or phosphate) Antirust agent (sodium nitrite, triethanolamine) Water Wetting agent, buffer, solubilizing agents, load-carrying agents	5

The Tool Engineers' Handbook[127] also presents a classification of cutting fluids based upon relative difficulty of machining operations, which is reproduced here as Table 11.

The oils shown in Table 11 are discussed below in order:

1. Ordinary soluble oils or emulsions—normal cutting mixtures, 1 part oil to 30 parts water. Grinding mixtures, 1 part oil to 30 to 50 parts water. Products of this class may, in their original state, be either oily or pasty but may be considered as emulsifiable petroleums, and their

TABLE 11


Oil 6
Oil 5
Oil 8
Oil 4
Oil 3
Oil 7
Oil 2
Oil 1
Low
Cutting Speed
High
Heavy
Depth of Cut
Light
Drawing
Broaching
Threading
Tapping
Generating
Hobbing
Shaping
Drilling
Turning
Boring
Milling
Difficult
Relative Difficulty of Machining Operations
Easy

mixtures emulsion of petroleum oils.

2. Supersoluble oils and compounds—normal mixtures, 15:1 to 50:1. Grinding mixtures, 30:1 to 100:1. These products are not too readily classified; in general, however, it may be said that they are products which form emulsions or solutions of higher cutting quality than those formed by petroleum emulsions.

3. Low-viscosity oils, kerosene, mineral seal, etc., and their mixtures with small amounts of fatty or other cutting bases, viscosities usually below 50 sec. at 100 degrees F. SUV (standard Saybolt Universal Viscosity). These light-bodied oils seem to be necessary in the machining of aluminum, magnesium, and similar metals and are sometimes used on other operations because of their fluidity and high cooling capacity.

4. Straight petroleums and mixtures with low percentages of fatty or other bases and with viscosities ranging from 75 to 150 sec. at 100 degrees F. SUV.

5. Mixtures of petroleum with from 10 to 30 per cent of fatty oil or with not more than 1 per cent active sulfur. Viscosity from 80 to 200 sec. at 100 degrees F. SUV.

6. Pure fatty oils, mixtures of petroleum and sulfur-bearing bases with up to two per cent active sulfur.

7. Sulfurized petroleum, sulfurized fatty mixtures with maximum sulfur activity.

8. Pigmented compounds mixed with oil or soaps to a pasty or semi-fluid consistency using pigment such as white lead, graphite, talc, or other unctuous pigments.

In addition to the above, the independent Research Committee on Cutting Fluids has published a table, "Recommended Cutting Fluids for Normal Machining Operations,"[128,40] which is reproduced here as Table 12. This table has the advantage that classifications of materials and machinability ratings are based on the same criteria employed in Table 2 of this chapter.

In the light of conflicting evidence it seems obvious that no simple theory will account in detail for the action of cutting fluids either as coolants or lubricants. Some observers have even proposed theories based on embrittlement via atomic penetration in the cutting zone.[149,150] Others have sought explanation in the possibility of electrochemical wear between tool and workpiece due to existence of thermoelectric and contact potentials.[148,151] The evaluation by the Battelle Memorial Institute[135] reaches the following significant conclusions:

1. In general a cutting fluid may act both as coolant and lubricant at low cutting speed and moderate depths of cut and feeds.

2. At the lower cutting speeds, below 100 revolutions per minute,

TABLE 12. RECOMMENDED CUTTING FLUIDS FOR NORMAL MACHINING OPERATIONS

Severity	Type of Machining Operation	*Ferrous Metals; Steels and Irons*				*Non-Ferrous Metals*	
		*I; 70% Plus**	*II; 50 to 70%**	*III; 40 to 50%**	*IV; Below 40%**	*V; 100% Plus**	*VI; Below 100%**
1 (Greatest)	Broaching; internal	Em. Sul. (a)	Sul. (b) Em.	Sul. Em.	Sul. Em.	MO. Em.	Sul. ML.
2	Broaching; surface	Em. Sul.	Em. Sul.	Sul. Em.	Sul. Em.	MO. Em.	Sul. ML.
2	Threading; pipe	Sul.	Sul. ML.	Sul.	Sul.		Sul. (c)
3	Tapping; plain	Sul.	Sul.	Sul.	Sul.	Em. Dry	Sul. ML.
3	Threading; plain	Sul.	Sul.	Sul.	Sul.	Em. Sul.	Sul.
4	Gear shaving	Sul. L.	Sul. L.	Sul. L.	Sul. L.		
4	Reaming; plain	ML. Sul.	ML. Sul.	ML. Sul.	ML. Sul.	ML. MO. Em.	ML. MO. Sul.
4	Gear cutting (d)	Sul. ML. Em.	Sul.	Sul.	Sul. ML.		Sul. ML.
5	Drilling; deep	Em. ML.	Sul. Em.	Sul.	Sul.	MO. ML. Em.	Sul. ML.
6	Milling; plain	Em. ML. Sul.	Em.	Em.	Sul.	Em. MO. Dry	Sul. Em.
6	Milling; multiple cutter	ML.	Sul.	Sul.	Sul. ML.	Em. MO. Dry	Sul. Em.
7	Boring; multiple head	Sul. Em.	Sul. Em.	Sul. Em.	Sul. Em.	K. Dry Em.	Sul. Em.
7	Multiple spindle automatic screw machines and turret lathes; drilling, forming, turning, reaming, cutting off, tapping, threading	Sul. Em. ML.	Sul. Em. ML.	Sul. Em. ML.	Sul. ML. Em.	Em. Dry ML.	Sul.
8	High speed, light feed automatic screw machines; drilling, forming, tapping, threading, turning, reaming, box milling, cutting off	Sul. Em. ML.	Sul. Em. ML.	Sul. Em. ML.	Sul. ML. Em.	Em. Dry ML.	Sul.
9	Drilling	Em.	Em.	Em.	Em. Sul.	Em. Dry	Em.
9	Planing, shaping	Em. Sul. ML.	Em. Sul. ML.	Sul. Em.	Em. Sul.	Em. Dry	Em.
9	Turning; single point tool form tools	Em. Sul. ML.	Em. Sul. ML.	Em. Sul. ML.	Em. Sul. ML.	Em. Dry ML.	Em. Sul.
10 (Least)	Sawing; circular, hack	Sul. ML. Em.	Sul. Em. ML.	Sul. Em. ML.	Sul. Em. ML.	Dry MO. Em.	Sul. Em. ML.
	Grinding; 1. plain	Em.	Em.	Em.	Em.	Em.	Em.
	2. form (thread, etc.)	Sul.	Sul.	Sul.	Sul.	MO. Sul.	Sul.

SYMBOLS FOR CUTTING FLUIDS
K.—Kerosene.
L.—Lard oil.
MO.—Mineral oils.
ML.—Mineral-lard oils.
Sul.—Sulfurized oils; see note (a).
Em.—Soluble or emulsifiable oils and compounds.
Dry—No cutting fluid.

Notes: * Machinability rating based on 100 per cent for cold-drawn Bessemer screw stock (specification B1112).
(a) Oils containing both sulfur and chlorine, when carefully manufactured and sponsored, may be used where sulfurized oils are indicated.
(b) Preferred recommendations are in bold face type.
(c) In threading copper, palm oil is frequently used.
(d) It is reported by several observers that emulsions are usually unsatisfactory on some precision machines, like Fellows gear shapers and Gleason gear generators.

and with light cuts, the film lubricating effect is likely to be predominant with the chemical film action becoming more important at the higher speeds and with heavier cuts.

3. At intermediate speeds, possibly from 100 to 250 surface feet per minute, both lubrication and cooling action seem to be important with the rate of cooling becoming increasingly so because of the problem of accessibility of the lubricant and the time factors in chemical film action. Boundary film action is very likely of minor importance in the upper portion of this range.

4. At even higher speeds conventional fluids are of little use even as coolants. This explains the efficacy of dry machining in so many cases with oxide and carbide tools at the speeds prevalent.

5. Of outstanding importance is the problem of accessibility of the fluid which is controlled by the point and method of application. In most cases, particularly at high speeds and heavy cuts, the preferred method appears to be via a thin jet or mist in the crevice along the side clearance face of the tool.

6. At the higher machining speeds the most effective coolants appear in approximate order to be—
   a. refrigerated gases (CO_2 and N_2),
   b. water (cold) with rust or corrosion inhibitors and preferably applied in the form of a spray,
   c. water solutions and soluble oils (preferably refrigerated).

It should be remembered that additives very probably are not effective except for protection or inhibiting chemical action.

There may be exceptions to the above generalization, particularly in the machining of malleable irons under conditions already noted, such that a type 1 chip is formed under brittle shearing action. Certainly this is true of ferritic malleable structures. The dividing line at which some lubrication becomes necessary depends on a variety of combinations of type of machining operation, material, tool, and machining conditions. The same is true of the general boundaries set forth in items 1 to 6 above. Until more is learned in a fundamental way about the mechanisms brought into play, choice must be determined by empirical methods using the latest evidence as a guide.

Promising leads for investigation appear to lie in the direction of experiments using realistic machine set-ups and tool conditions, but designed to reveal the nature of the fundamental mechanisms and heat transfer processes concerned. Much can be accomplished by exploration coupled with theory and analytical methods with the use of modern electronic instrumentation thermocouples, strain gauges, and multichannel recorders.

TYPICAL MACHINING OPERATIONS

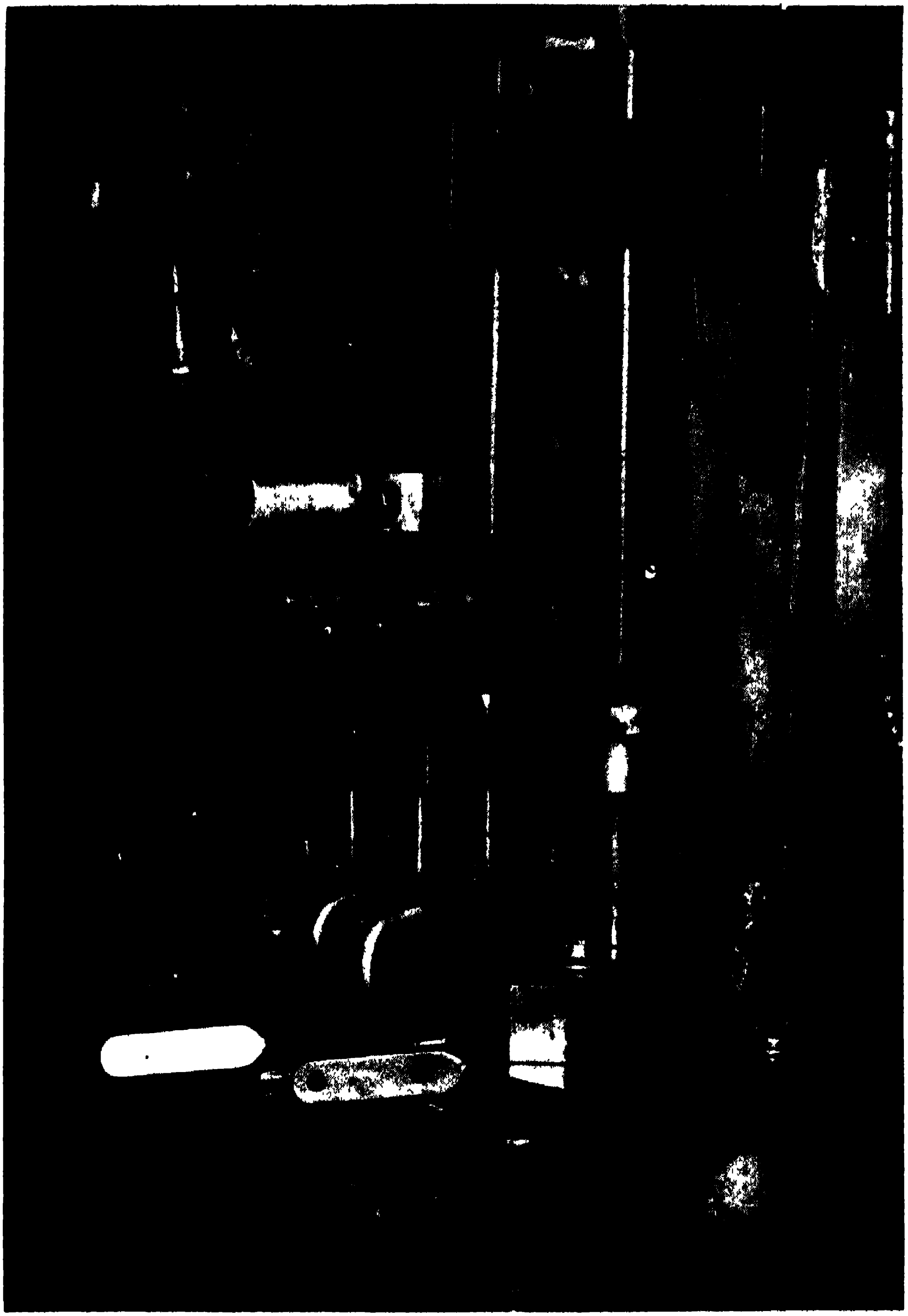
In the light of the foregoing discussions, this section will present a series of machining techniques, illustrated with plates and full supporting data. These have been chosen after thorough study and with the collaboration of a number of Malleable Founders' Society member foundries and are regarded as typical of practices as they exist in industry.

Each of the ensuing subsections deals with a particular grade of malleable iron, illustrating as many as possible of the different machining operations which can be performed on the part. All of the grades of both ferritic and pearlitic malleable iron are presented in the sequence with multiple operations being performed. Drawings are accurately to scale, which is indicated. Notes and data in boxes give sufficient detail for complete tooling and duplication of the processes, if desired. Material removed in the operation is shown by shaded areas. Insert tool bits are highlighted in a similar manner. Rake and clearance angles are given where pertinent, along with other critical tool design information. Feeds, speeds, and representative tool life are included.

These illustrations should not be regarded as representing the only method of accomplishing the results with malleable iron. They are, however, presented as typical and do represent what is regarded as current practice in industry.

The reader should find the data given sufficiently complete to assist in carrying out any machining operations desired. Illustrations are also intended to give sufficient insight to enable users of this handbook to plan other applications based upon these procedures.

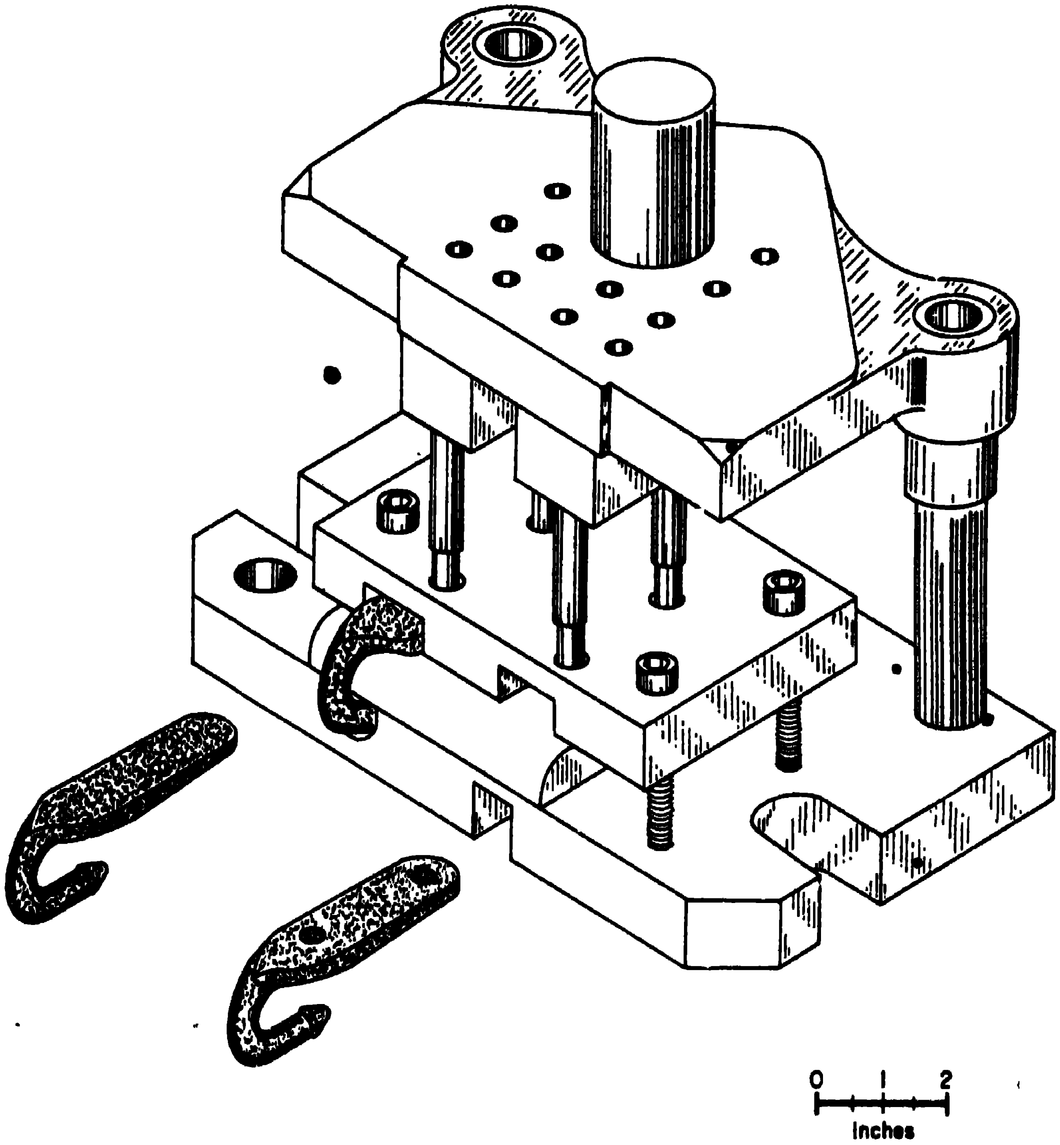
NOTE: In the following Case Histories, mention of a typical cutting tool specification is not to be misconstrued as a recommendation for a specific brand. Tools of comparable composition and equivalent geometry, made by other manufacturers, can be used with equal success.



Case History 1

Rope Hook (Grade 32510)

Machining involves a punching operation; tool life approximates two shifts.



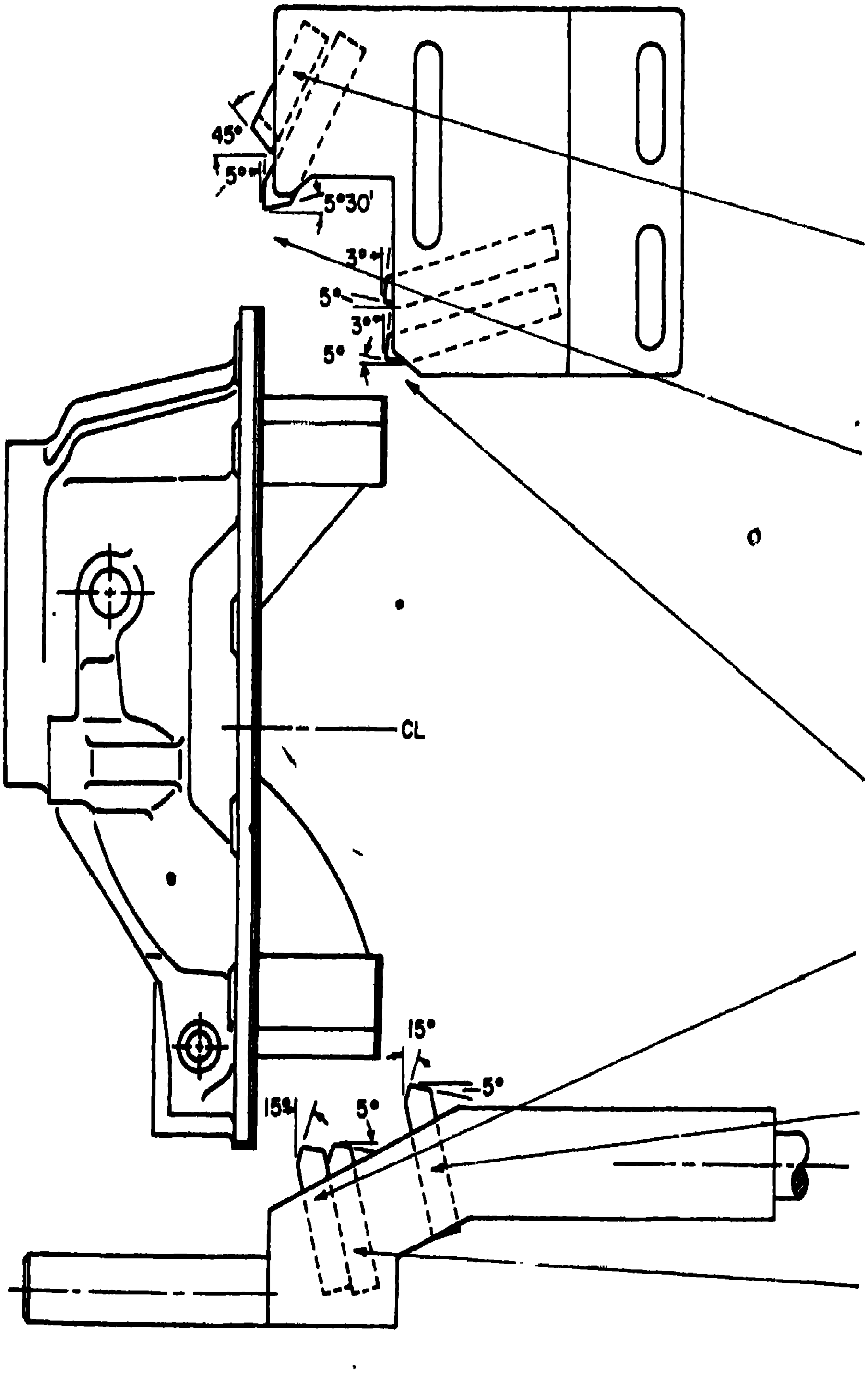
Mach Data	Tool Data
45 Ton Punch Press	Pierce Two Holes
Self Contained Die	HSS Punches & Button Dies
Diam 11/32	
	Production 1800 Pcs Per Hr
	Tool Life 15000 Pcs Per Grind

Case History 2

Differential Carrier

The series of operations depicted on the following pages affords an excellent illustration of machining on the casting shown above which is in quantity production for the automotive industry. Note the extreme variations in cross-section and the manner in which the part is designed to lend itself to ease of machining.

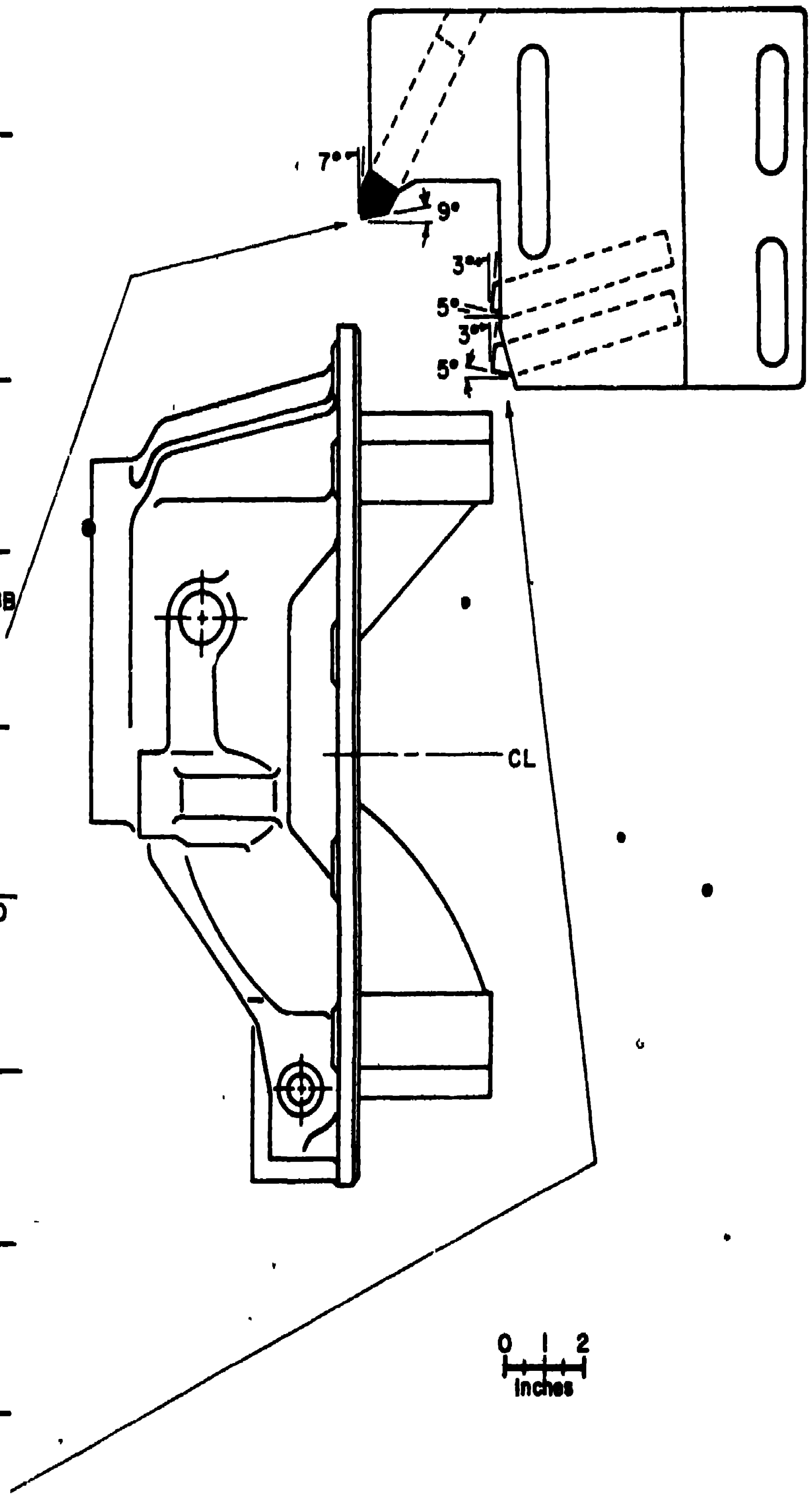
This part is supplied in a ferritic malleable iron, grade 32510. A total of ten cuts, seven rough and three finish, are shown on this part requiring three passes. The drawings following detail the five subsequent operations, which include milling, drilling, reaming, counter-boring, chamfering, and tapping.



Mach Data

Single Spindle Automatic Lathe

rpm	28
fpm	133
Length Cut	45°
Depth Cut	1/16
rpm	28
fpm	133
fpr	0.028
Length Cut	2 1/2
Depth Cut	1/4
rpm	28
fpm	133
fpr	0.045
Length Cut	3 1/4
Depth Cut	1/32
rpm	28
fpm	118
fpr	0.028
Length Cut	2 1/2
Depth Cut	1/16
rpm	28
fpm	133
fpr	0.035
Length Cut	2 5/8
Depth Cut	1/4
rpm	28
fpm	118
fpr	0.035
Length Cut	2 5/8
Depth Cut	1/4
rpm	28
fpm	133
fpr	0.035
Length Cut	5/8
Depth Cut	1/8
rpm	28
fpm	118
fpr	0.045
Length Cut	2 1/2
Depth Cut	0.020



Tool Data

Chamf Flange OD
Stellite 98 M
Tool Life 200 Pcs
Per Grind

Rgh Face Flange
XC 4 Rex Alloy
Tool Life 40 Pcs
Per Grind

Fin Face Flange
Carboloy 1340GR78B
Tool Life 200 Pcs
Per Grind

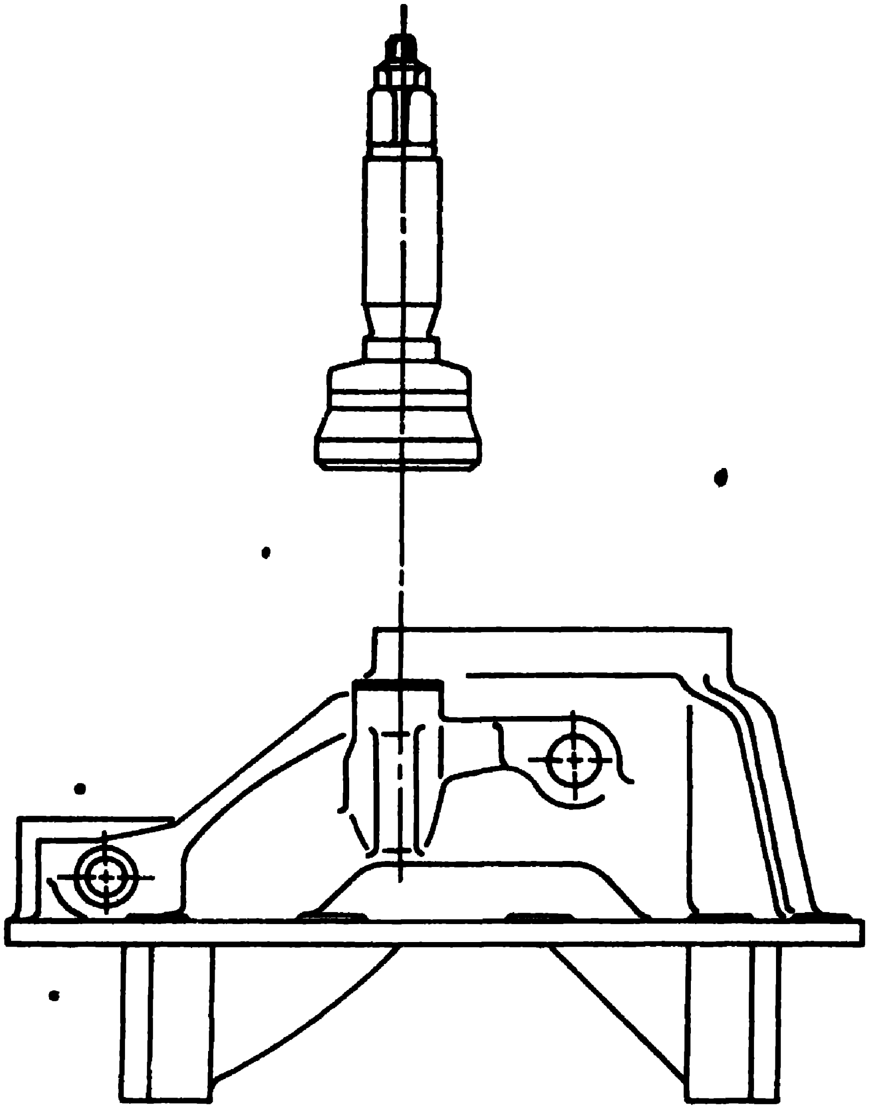
Rgh Face Pedestals
M3 D HSS
Tool Life 40 Pcs
Per Grind

Rgh Turn Flange OD
XC 3 Rex Alloy
Tool Life 45 Pcs
Per Grind

Turn Pedestal
Clearance
M3D HSS
Tool Life 40 Pcs
Per Grind

Fin Turn Flange OD
M3D HSS
Tool Life 200 Pcs
Per Grind

Fin Face Pedestals
M3D HSS
Tool Life 200 Pcs
Per Grind

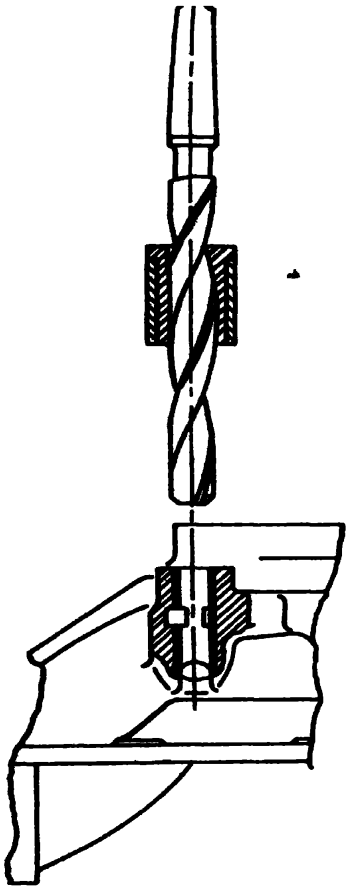


1st Operation

Mach Data		Tool Data
rpm	273	End Mill Boss
fpm	250	Shell End Mill TBC35R
fpr	0.028	Carbide Tipped
Feed	0.047	Insert Tool
Length Cut	1 7/8	Tool Life 800
Depth Cut	3/16	Pcs Per Grind

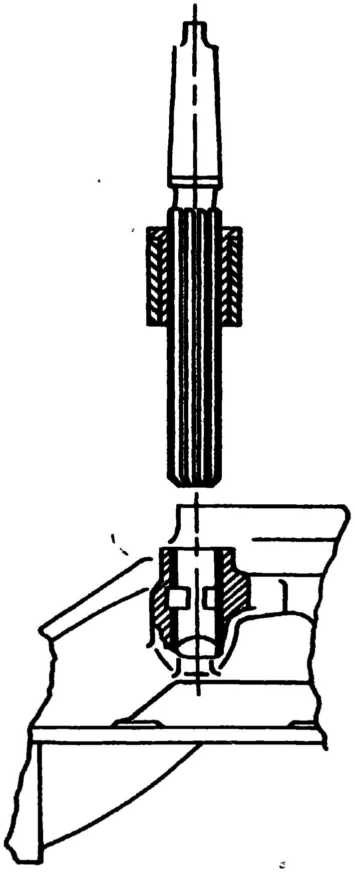
0 1 2

Inches



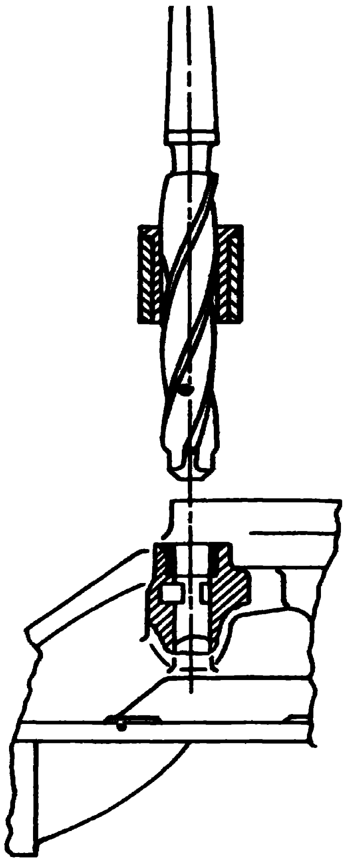
2nd Operation

Mach Data		Tool Data
rpm	288	Drill Cored Hole
fpm	65	HSS RC63-65
fpr	0.0197	Tool Life 50 Pcs
LengthCut	1 3/4	Per Grind
DepthCut	15/64	



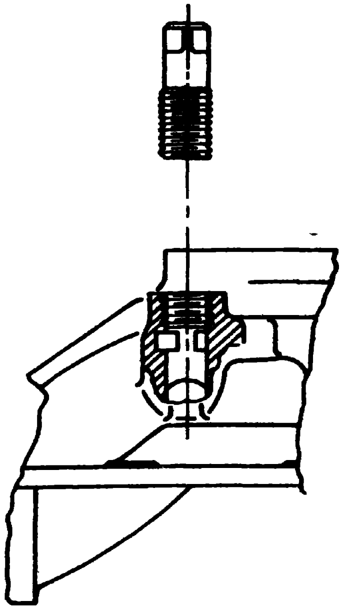
3rd Operation

Mach Data		Tool Data
rpm	153	Ream Drilled
fpm	45	Hole
fpr	0.0286	HSS RC62-64
Feed	0.036	Tool Life 300
Length Cut	3 1/2	Pcs Per Grind
Depth Cut	0.015	



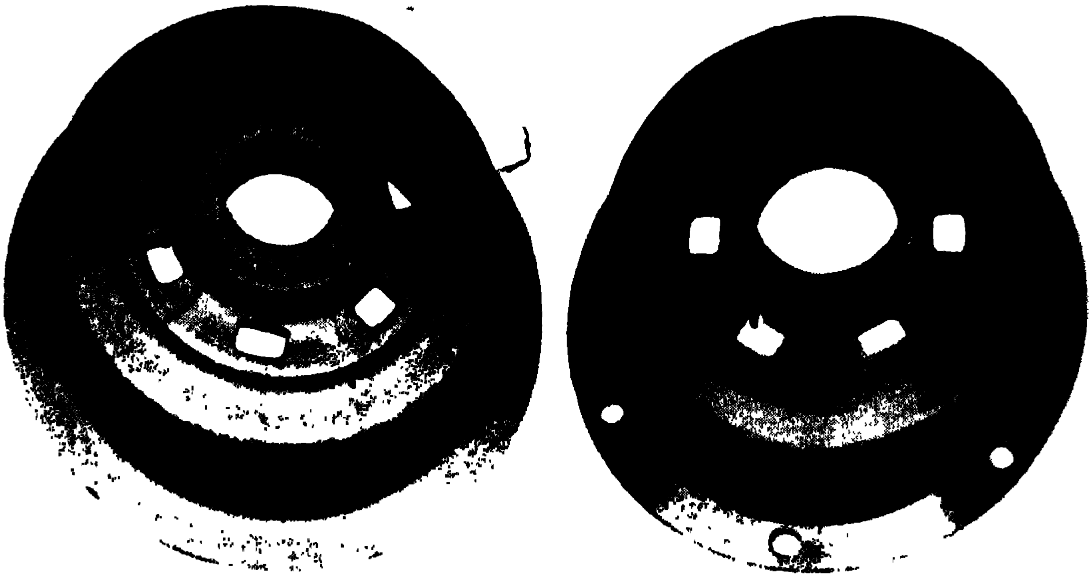
4th Operation

Mach Data		Tool Data
rpm	116	Counterbore &
fpm	36	Chamf Reamed
fpr	0.044	Hole
Feed	0.011	HSS Twist Drill
Length Cut	1.0	0.938
Depth Cut	0.024	Tool Life 300
		Pcs Per Grind



5th Operation

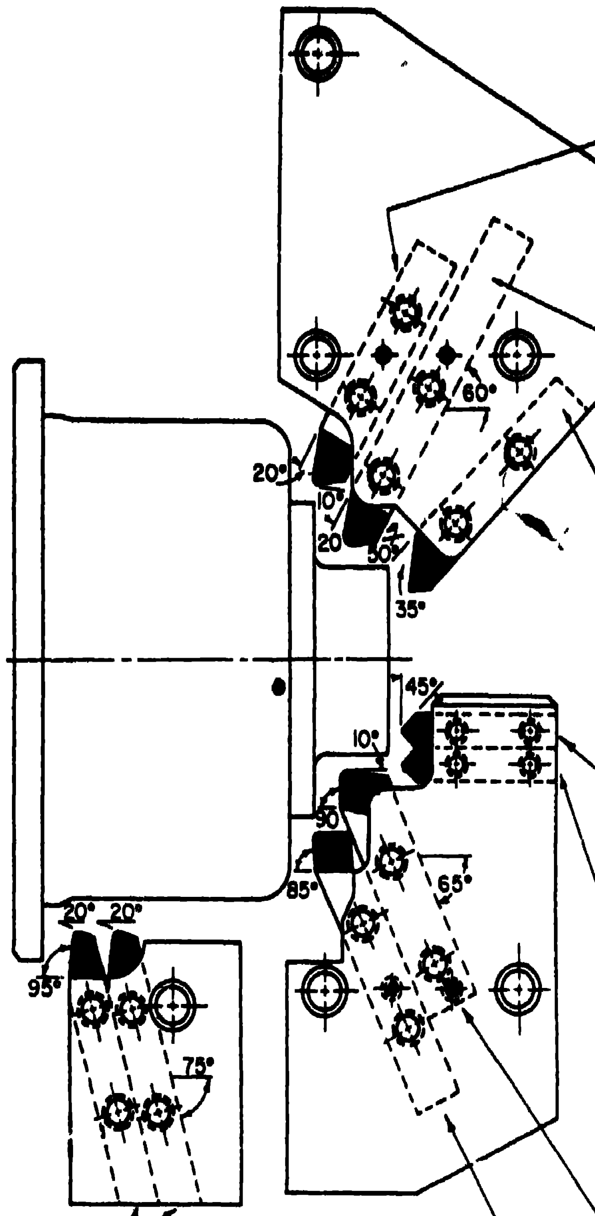
Mach Data		Tool Data
rpm	117	Tap One Inch
fpm	36	Counterbored
LengthCut	11/16	Hole
		Tapping Head
		Tool Life 2500
		Pcs Per Grind



Case History 3

Gear Support Case

This is another example of a fairly large casting (approximately 9 in. diameter x 6 in. deep) on which a complex series of rough turning and finishing operations is performed in three steps. A high-strength, medium-elongation grade of pearlitic malleable iron is employed to meet the service requirements. The sequences afford an excellent illustration of standard practice in the use of carbide tools.



Mach Data		Tool Data
rpm	236	Face Clearance
fpm	415	Carboloy 907
fpr	0.0094	Rake 0°
Depth Cut		3/4×15/32
0.016		Insert
Cycle	0.72 Min	Tool Life 150 Pcs
rpm	236	Face Hub Shoulder
fpm	223	Firthite B-33-8TA
fpr	0.0094	Rake 0°
Depth Cut		1×1/2 Insert
0.125		Tool Life 150 Pcs
Cycle	0.72 Min	
rpm	236	Face Hub End
fpm	176	Carboloy 907
fpr	0.0094	Rake 0°
Depth Cut		1/2×3/4 Insert
0.125		Tool Life 150 Pcs
Cycle	0.72 Min	
rpm	236	Chamf I D Hub
fpm	176	Carboloy 907
fpr	0.0094	Rake 0°
Depth Cut		3/4×15/32
0.125		Insert
Cycle	0.72 Min	Tool Life 150 Pcs
rpm	236	Chamf OD Hub
fpm	176	Carboloy 907
fpr	0.0094	Rake 0°
Depth Cut		1/2×1/2 Insert
0.125		Tool Life 150 Pcs
Cycle	0.72 Min	
rpm	236	Turn 2.765 Diam
fpm	176	Carboloy 907
fpr	0.0094	Rake 0°
Depth Cut		1/2×1/2 Insert
0.125		Tool Life 150 Pcs
Cycle	0.72 Min	

Mach Data		Tool Data
rpm	236	Turn 7.265 Diam
fpm	464	Carboloy 907
fpr	0.0094	Rake 0°
Depth Cut		1/2×3/4 Insert
0.125		Tool Life 150 Pcs
Cycle	0.72 Min	
rpm	36	Turn 4.725 Diam
fpm	464	Carboloy 907
fpr	0.0094	Rake 0°
Depth Cut		1/2×3/4 Insert
0.125		Tool Life 150 Pcs
Cycle	0.72 Min	

5 Stn Horizontal Chucking Machine

Rough Casting Weight	21.4 Lb
Machined Casting Weight	14.2 Lb

0 1 2
Inches

Case History 4

Cable Clamp

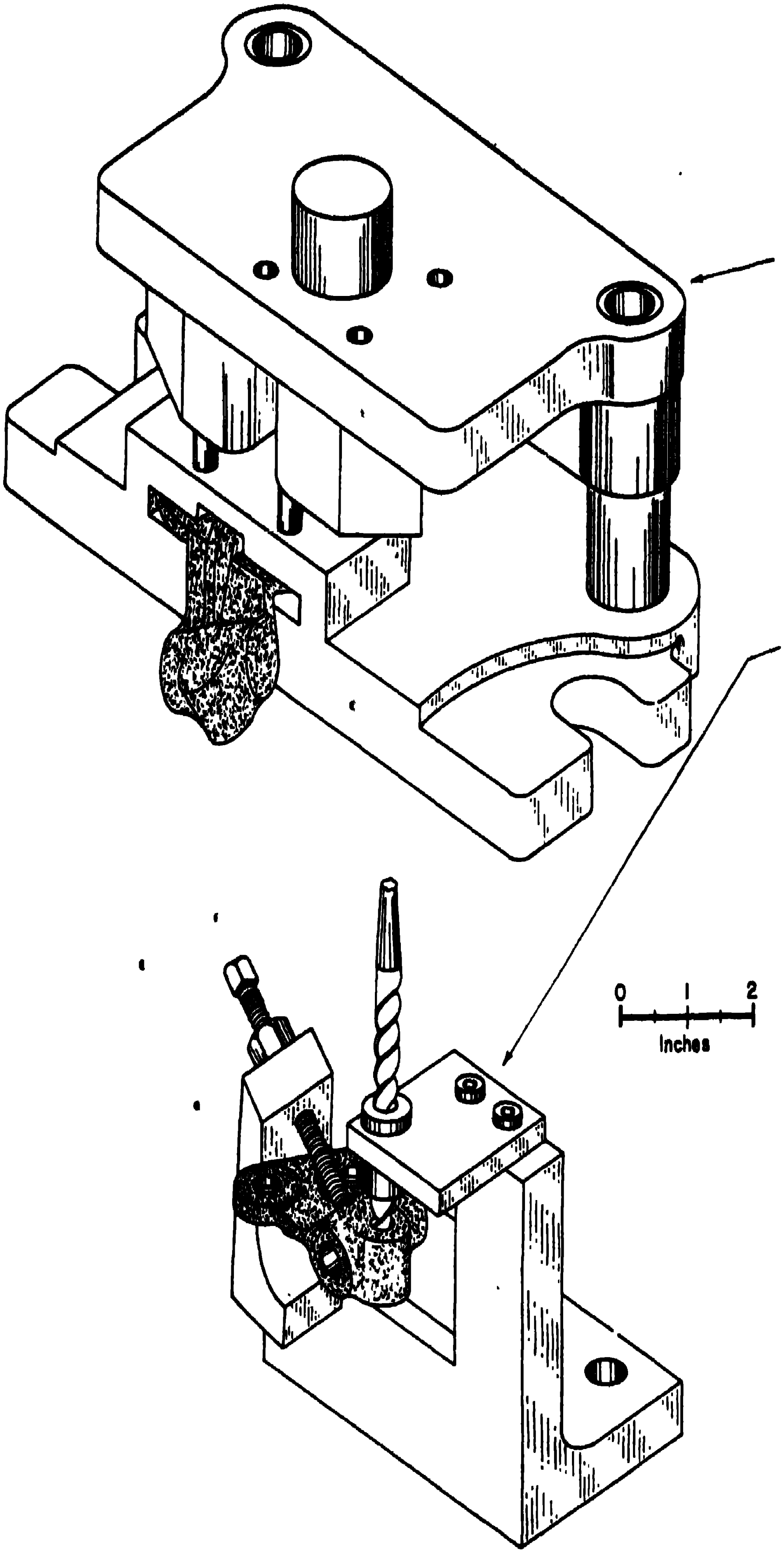
This illustrates four operations on a cable clamp.

The first step of punching two holes clearly shows the ease of working a ferritic malleable iron, both from the standpoint of tool life and production rate.

Drilling procedure is typical of conservative practice and indicates a good balance of production rate and tool life. Drills are very readily replaced.

In the case of the milling operation, note that tool life approximates two full shifts at a very high production rate. Milling cutters are relatively more difficult to grind for exchange.

All these steps are typical for high speed steel tools, which are still in most common use for such work.



Mach Data

25 Ton Punch Press
Self Contained Die

Diam	11/32

Four Spindle Hydraulic
Drill Press With Pump
Handle Jigs

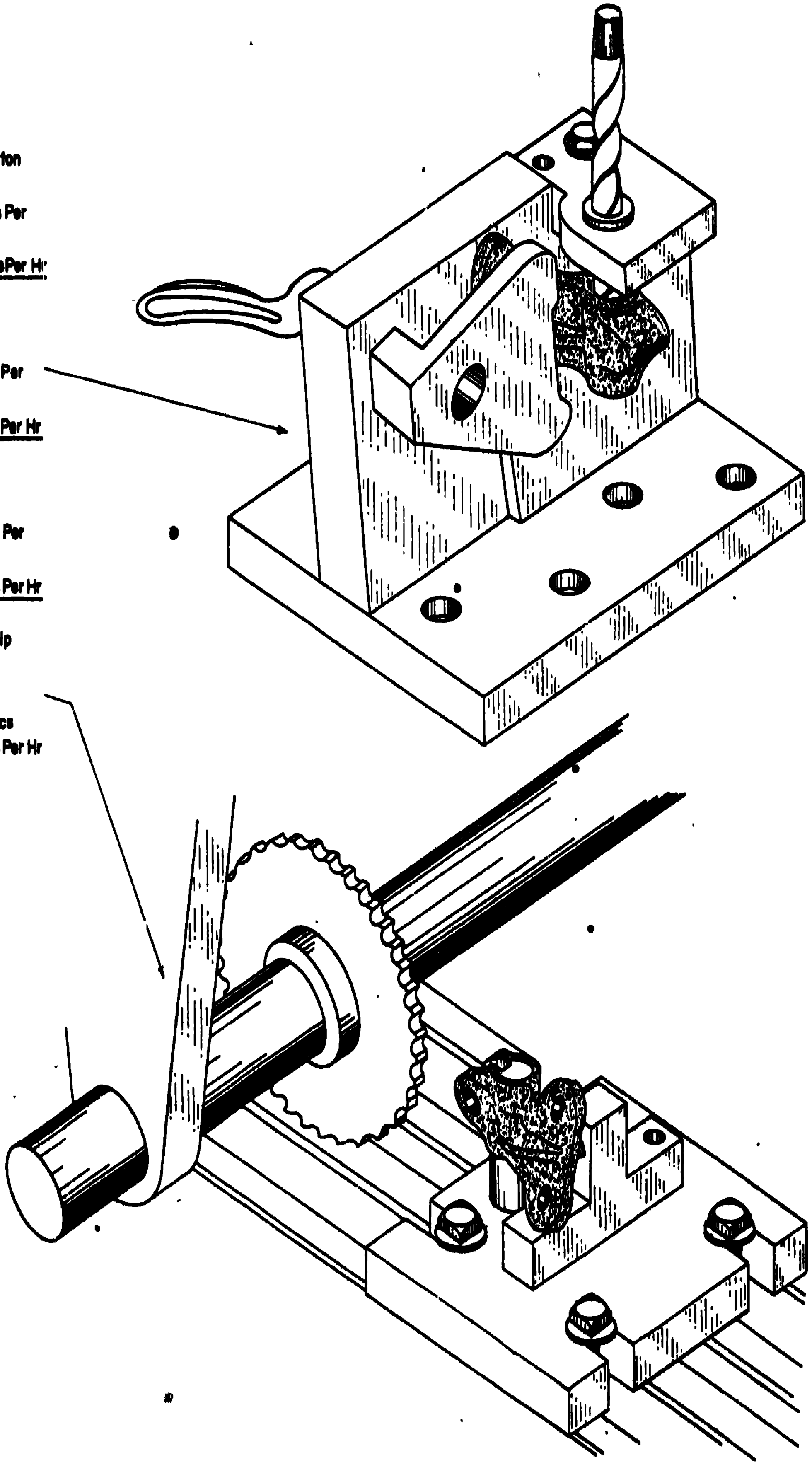
rpm	1200
ipr	0.009
Diam	0.443

Two Spindle Air Feed With
Pin Locating Fixtures

rpm	1200
ipr	0.009
Diam	0.328

Horizontal Milling Mach
With Air Feed & Pin
Locating Fixture

rpm	200
ipm	28.5
Width	7/32



Tool Data

Pierce Two Holes
HSS Punches & Button Dies
Tool Life 2400 Pcs Per Grind
Production 1000 Pcs Per Hr

Drill Hole
HSS Drills
Coolant Soluble Oil
Tool Life 1000 Pcs Per Grind
Production 500 Pcs Per Hr

Drill Hole
HSS Drills
Coolant Soluble Oil
Tool Life 1400 Pcs Per Grind
Production 700 Pcs Per Hr

Saw Slot
4X7/32 Triple Chip 36 Tooth Saw
Coolant Soluble Oil
Tool Life 10000 Pcs
Production 650 Pcs Per Hr

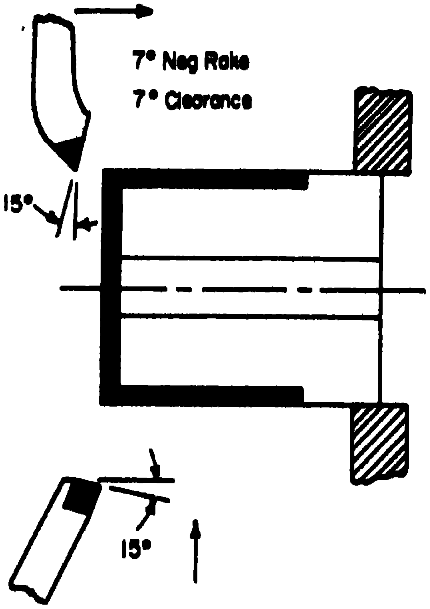
Case History 5

Worm Lift Gear

This part is made in a high-strength, medium-elongation grade of pearlitic malleable iron to obtain the necessary wear characteristics without induction or flame hardening of the worm, an operation which is difficult and expensive to achieve. The five multiple operations again demonstrate a balance of production rate and tool life with the use of carbide insert tools. Of particular interest is the machining of the 47.1 inch long worm in the fifth operation.

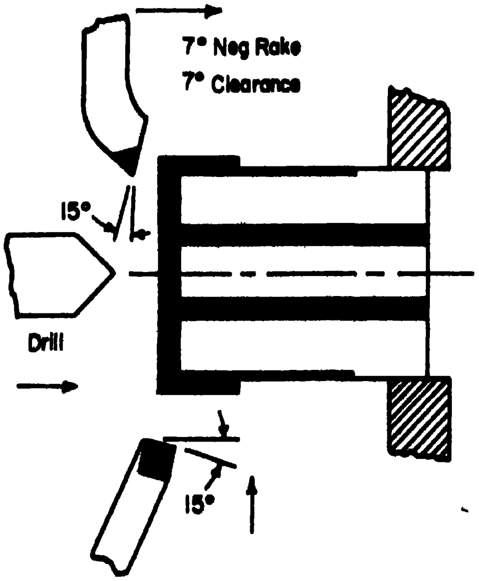
1st Operation

Mach Data		Tool Data
Six Station Semi Automatic Turret Lathe rpm fpm fpr OD Depth Cut	 176 170 0.011 3 1/2 1/4	Rgh Turn Vascoloy Ramet 2A5 Insert Mechanically Held Steel Holder Tool Life 25 Pcs Per Edge
rpm fpm fpr Depth Cut	176 170/69 0.011 1/4	Rgh Face Vascoloy Ramet 2A5 Insert Mechanically Held Steel Holder Tool Life 25 Pcs Per Edge



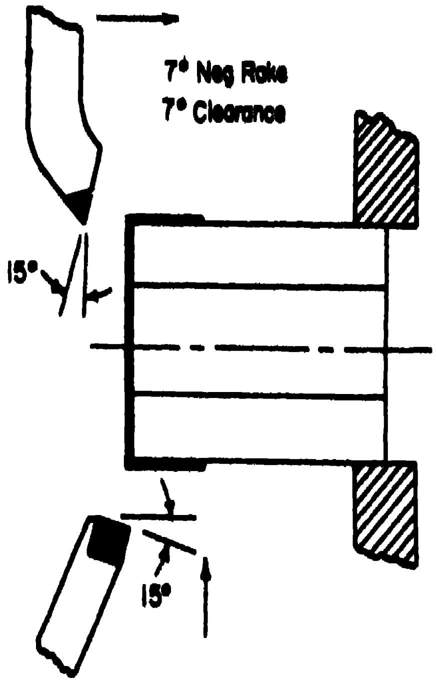
2nd Operation

Mach Data		Tool Data
Six Station Semi Automatic Turret Lathe rpm fpm fpr Diam	 176 53 0.007 1 13/32	Spot Drill & Drill HSS Drill Tool Life 100 Pcs Per Grind
rpm fpm fpr OD Depth Cut	176 170/169 0.007 - 0.011 3 1/2 1/4	Rgh Turn & Rgh Face Vascoloy Ramet 2A5 Insert Mechanically Held Steel Holder Tool Life 25 Pcs Per Edge
rpm fpm fpr Depth Cut	304 112 0.007 1/4	Rgh Bore & Chamf ID Carboloy 883 Brazed Tip Steel Holder Tool Life 25 Pcs Per Edge
rpm fpm fpr Depth Cut	249 228/96 0.015 1/32	Fin Bore Fin Face & Fin Turn Carboloy 883 Brazed Tip Steel Holder Tool Life 25 Pcs Per Edge
rpm fpm fpr	304 112 0.034	Ream HSS Reamer Tool Life 100 Pcs Per Grind



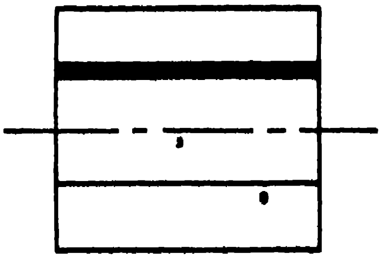
3rd Operation

Mach Data		Tool Data
Six Station Turret Lathe		Fin Turn
rpm	249	Vascoloy Ramet 2A5
fpm	228	Insert
fpr	0.015	Mechanically Held
Depth Cut	1/32	Steel Holder
		Tool Life 25 Pcs Per Edge
rpm	249	Fin Face
fpm	228/100	Vascoloy Ramet 2A5
fpr	0.0075	Insert
Depth Cut	1/32	Mechanically Held
		Steel Holder
		Tool Life 25 Pcs Per Edge



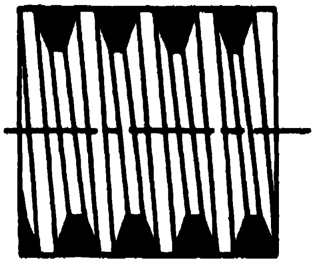
4th Operation

Mach Data		Tool Data
3 1/2 Inch Horizontal		Broach Keyway
Broaching Mach		HSS Broach
fpm	2 1/2	
Feed	0.003	
Depth Cut	0.145	



5th Operation

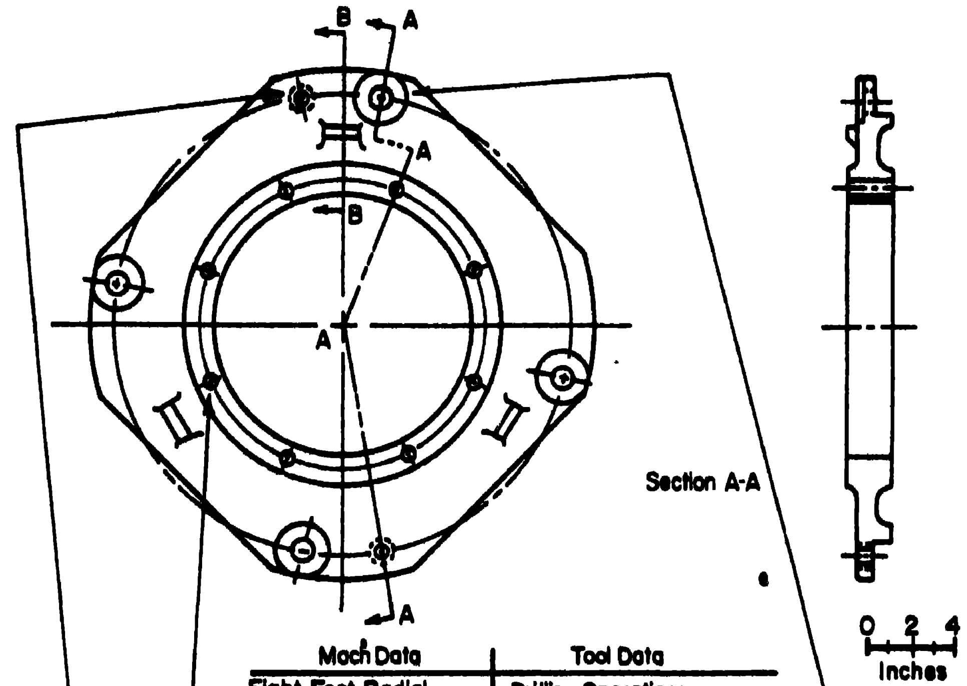
Mach Data		Tool Data
Hobbing Mach		Hob Worm
rpm	93	18 Tooth Single Cutter
Feed	0.0027	HSS
		Length Of Worm 471



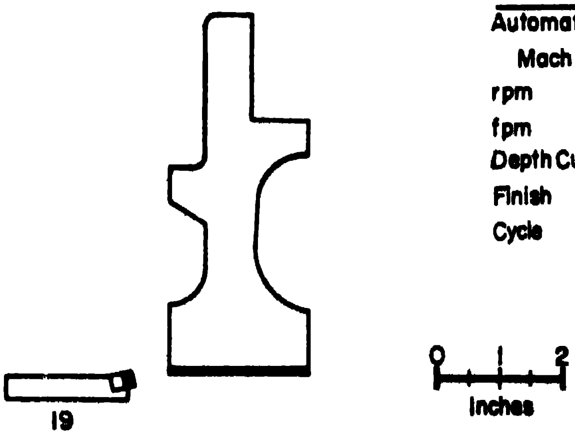
Case History 6

Motor Frame Head

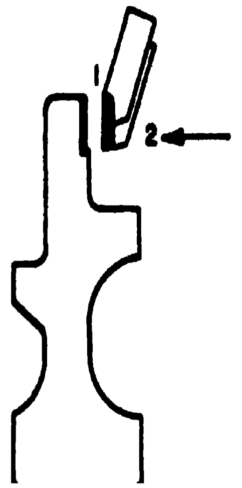
This pearlitic malleable iron frame head carries the armature shaft bearing in an electric motor used on oil well drilling equipment. It supplies an excellent illustration of what can be accomplished with pearlitic malleable iron in a large casting and, if necessary, large sections. Two feet in diameter and over two inches thick at the heaviest section, this part has an interesting sequence of machining steps including step plunge cutting, facing, rough turning and finishing. A three-machine set-up is used. These are regulated in speed so that only one operation is required. The part formerly cast in another material can now be machined with a 20 per cent reduction in cost.

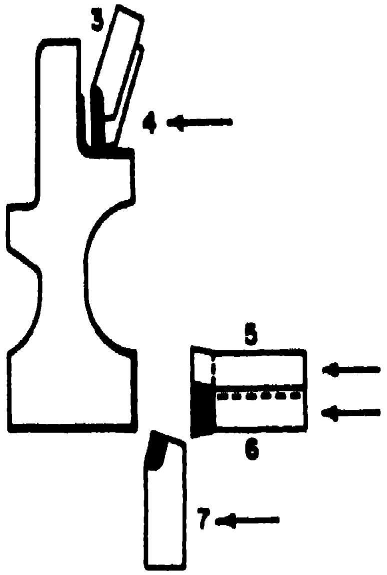


Mach Data		Tool Data
Eight Foot Radial		Drilling Operations
Drill		Coolant Soluble Oil
Cycle	5	
rpm	257	Drill Four Holes 1 1/16 Diam
Feed	0.021	
rpm	109	Counterbore 2 1/2 Diam
Feed	0.021	
rpm	340	Drill Eight Holes 1 1/16 Diam
Feed	0.021	
rpm	309	Countersink Two Holes
Feed	0.021	
rpm	390	Tap Two Holes & Countersink Tap 1-8
Feed	0.021	



Mach Data		Tool Data	
Automatic Boring		Tool Set Up For Fin Boring	
Mach		Tool 19 Carboloy CSFR-12 GR 0-30 Oxide	
rpm	306		
fpm	1000	Back Rake	5°
Depth Cut	0.010 0.015	Side Rake	5°
Finish	25-32	End Relief	5°
Cycle	2	Side Relief	5°
		End Cutting Edge	15°
		Side Cutting Edge	15°
		Nose Rad	1/32



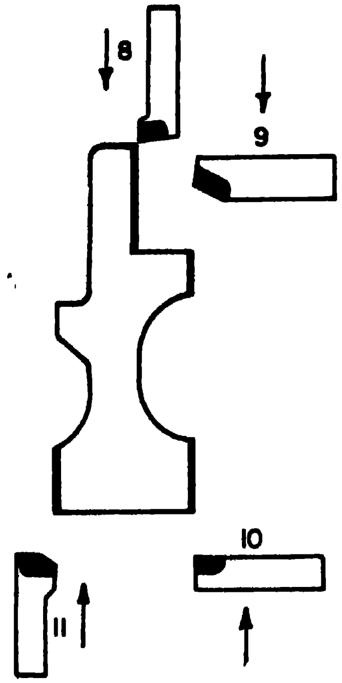


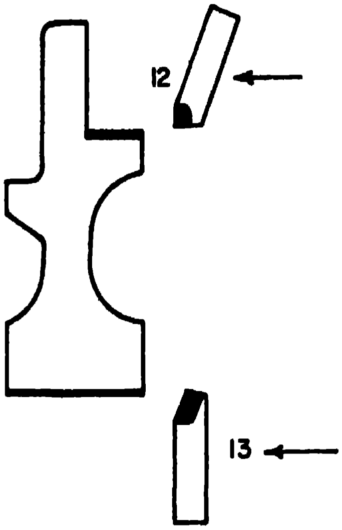
1st Station

Mach Data		Tool Data	
Automatic Turret Lathe		Step Plunge Cut Flange	
rpm	22	Face	
Feed	0.007	Coolant Soluble Oil	
Depth Cut	3/32	Tool 1&2 Carboloy	
Cycle	28	BL-16 GR44A	
		Back Rake	0°
		Side Rake	6°
		End Relief	7°
		Side Relief	7°
		End Cutting Edge	8°
		Side Cutting Edge	15°
		Nose Rad	1/16

2nd Station

Mach Data		Tool Data (Cont)	
Automatic Turret Lathe		Tool 5 & 6 Carboloy	
rpm	41	C-16 GR44A	
Feed	0.007	Back Rake	0°
Depth Cut	3/32	Side Rake	0°
Cycle	28	End Relief	7°
		Side Relief	7°
Tool Data		End Cutting Edge	0°
Step Plunge Cut Flange		Side Cutting Edge	0°
Face & Rgh Turn Flt		Tool 7 Carboloy	
Diam		BR-16 GR 44A	
Coolant Soluble Oil		Back Rake	0°
Tool 3&4 Carboloy		Side Rake	6°
BL-16 GR44A		End Relief	7°
Back Rake	0°	Side Relief	7°
Side Rake	6°	End Cutting Edge	8°
End Relief	7°	Side Cutting Edge	15°
Side Relief	7°	Nose Rad	1/16
End Cutting Edge	8°		
Side Cutting Edge	15°		
Nose Rad	1/16		





3rd Station

Mach Data	
Automatic Turret Lathe	
rpm	41
Feed	0.007
Depth Cut	1/16
Cycle	28

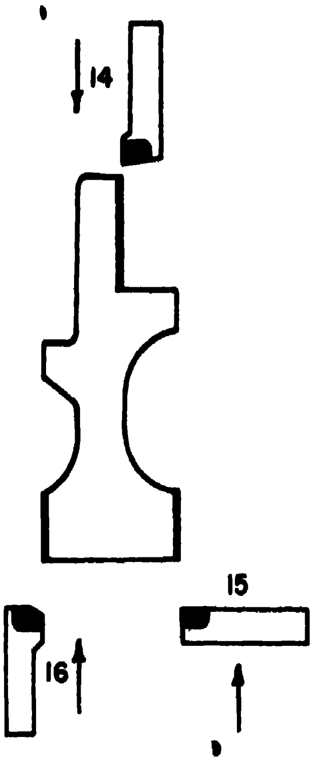
Tool Data	
Rgh Face Flange & Face	
Coolant Soluble Oil	
Tool 8 & 9 On Cross Slide	
Rgh Face Hub Front & Back	
Tool 10 & 11 On Turret Slide	
Tool 8 Carboloy	
FL-16 GR883	
Back Rake	6°
Side Rake	0°
End Relief	7°
Side Relief	7°
End Cutting Edge	0°
Side Cutting Edge	8°
Nose Rad	1/16
Tool 9 Carboloy	
BR-16 GR883	

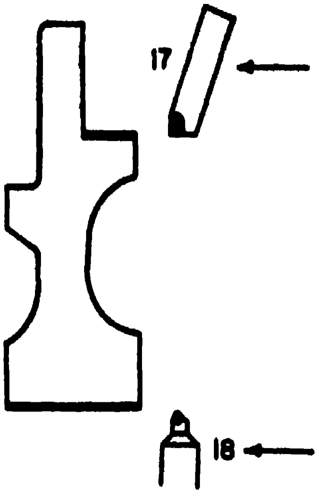
Tool Data (Cont)	
Back Rake	0°
Side Rake	6°
End Relief	7°
Side Relief	7°
End Cutting Edge	8°
Side Cutting Edge	15°
Nose Rad	1/16
Tool 10 Carboloy	
AL-12 GR 883	
Back Rake	0°
Side Rake	6°
End Relief	7°
Side Relief	7°
End Cutting Edge	8°
Side Cutting Edge	0°
Nose Rad	1/16
Tool 11 Carboloy	
FL-16 GR883	
Back Rake	6°
Side Rake	0°
End Relief	7°
Side Relief	7°
End Cutting Edge	15°
Side Cutting Edge	8°
Nose Rad	1/16

Mach Data	
Automatic Turret Lathe	
rpm	73
Feed	0.007
Depth Cut	1/16
Cycle	28

Tool Data	
Semi Fin Turn Fit Diam & Semi Fin Bore	
Coolant Soluble Oil	
Tool 12 Carboloy	
BL-12 GR883	
Back Rake	0°
Side Rake	6°
End Relief	7°
Side Relief	7°

Tool Data (Cont)	
End Cutting Edge	8°
Side Cutting Edge	15°
Nose Rad	1/16
Tool 13 Carboloy	
BR-12 GR883	
Back Rake	0°
Side Rake	6°
End Relief	7°
Side Relief	7°
End Cutting Edge	8°
Side Cutting Edge	15°
Nose Rad	1/16





5th Station

Mach Data	
Automatic Turret Lathe	
rpm	73
Feed	0.007
Depth Cut	1/32
Cycle	28

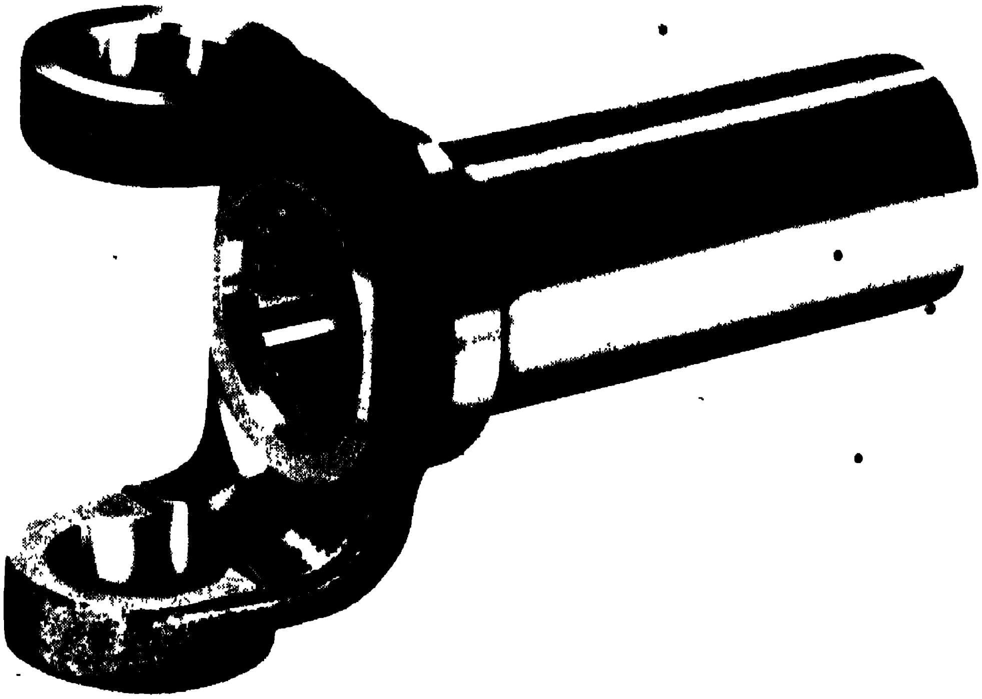
Tool Data	
Fin Flange Face & Fin Face Hub Front & Back	
Coolant Soluble Oil	
Tool 14 Carboloy FL-16 GR 883	
Back Rake	6°
Side Rake	0°
End Relief	7°
Side Relief	7°
End Cutting Edge	0°
Side Cutting Edge	8°
Nose Rad	1/32

Tool Data (Cont)	
Tool 15 Carboloy AL-16 GR 883	
Back Rake	0°
Side Rake	6°
End Relief	7°
Side Relief	7°
End Cutting Edge	8°
Side Cutting Edge	0°
Nose Rad	1/32
Tool 16 Carboloy FL-16 GR 883	
Back Rake	6°
Side Rake	0°
End Relief	7°
Side Relief	7°
End Cutting Edge	15°
Side Cutting Edge	8°
Nose Rad	1/32

6th Station

Mach Data	
Automatic Turret Lathe	
rpm	73
Feed	0.007
Depth Cut	1/32
Cycle	28
rpm	133
Feed	0.007
Cycle	28

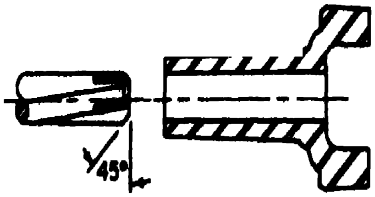
Tool Data	
Semi Turn Fit Diam	
Coolant Soluble Oil	
Tool 17 Carboloy BL-12 GR 883	
Back Rake	0°
Side Rake	6°
End Relief	7°
Side Relief	7°
End Cutting Edge	8°
Side Cutting Edge	15°
Nose Rad	1/32
Semi Fin Bore	
Coolant Soluble Oil	
Tool 18 Micro Bore Unit GR 330	
Back Rake	0°
Side Rake	0°
End Relief	5°
Side Relief	5°
End Cutting Edge	10°
Side Cutting Edge	10°
Nose Rad	1/32



Case History 7

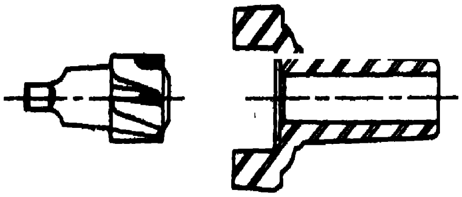
Universal Slip Yoke

This part is manufactured in a very high-strength pearlitic malleable iron to meet the severest requirements of service. A wide range of operations is shown including core drilling, face milling, broaching, boring, turning, drilling and grinding. Note the use of carbide tipped core drills and spot facers in several of the steps. This series illustrates a number of modern practices with both carbide and high speed steel tools.



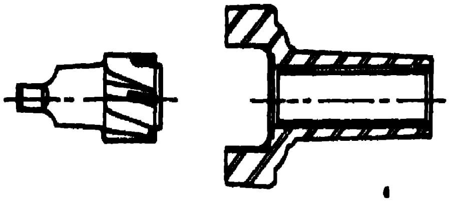
1st Operation

Mach Data		Tool Data
rpm	500	Core Drill Body Hole
fpm	44	Carbide Core Drill
fpr	0.031	Three Fluted
Diam		Coolant Soluble Oil
Depth Cut	3/32	Carboloy 883
		Tool Life 150 Pcs Per
		Grind 4500 Per Tool



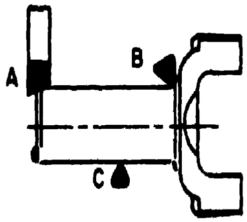
2nd Operation

Mach Data		Tool Data
rpm	362	Rgt. Spotface Yoke End
fpr	0.020	Carbide Tipped
		Spotfacer
		Coolant Soluble Oil
		Carboloy 883
		Tool Life 300 Pcs Per
		Grind 3000 Per Tool



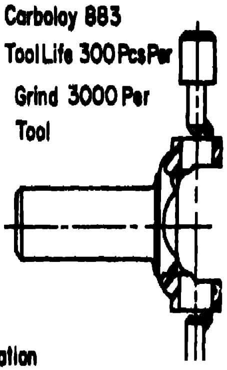
5th Operation

Mach Data		Tool Data
rpm	362	Fin Spotface & Counter
fpr	0.020	Bore Yoke End
		Carbide Tipped
		Spotfacer
		Coolant Soluble Oil
		Carboloy 883
		Tool Life 300 Pcs Per
		Grind 3000 Per
		Tool



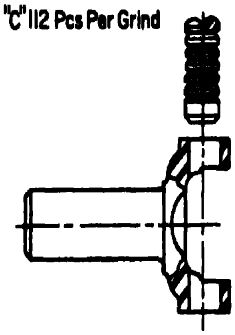
6th Operation

Mach Data		Tool Data
rpm	511	Fin Turn Stem
fpm	288	Kenna Metal K4H
fpr	0.030	Tool Life
Back Tooth Feed		"A" 700 Pcs Per Grind
0.011		"B" 112 Pcs Per Grind
Depth Cut	0.040	"C" 112 Pcs Per Grind



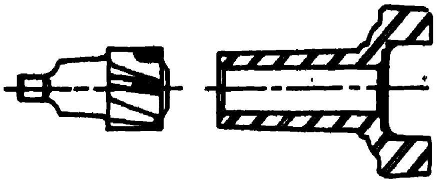
9th Operation

Mach Data		Tool Data
rpm	1300	Qualify Bore Cross
fpr	0.004	Hole
Depth Cut	0.021	Carboloy 350
		Coolant Soluble Oil
		Solid Carbide Boring
		Tools



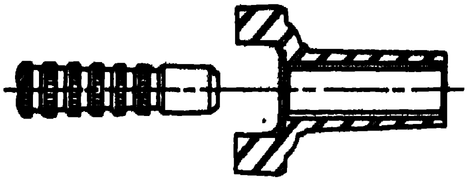
10th Operation

Mach Data		Tool Data
fpm	18	Broach Cross Hole
Depth Cut	0.010	HSS Broach
0.003 Per Tooth		1.062 Diam
Length Of Cut	1 1/4	Coolant Cutting Oil
		Tool Life 1200 Pcs
		Per Grind



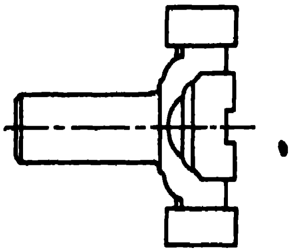
3rd Operation

Mach Data		Tool Data
rpm	362	Fin Face Stem End
fpr	0.020	Carbide Tipped
		Spotfacer
		Coolant Soluble Oil
		Carboloy 883
		Tool Life 500 Pcs
		Per Grind



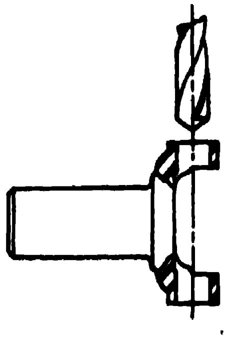
4th Operation

Mach Data		Tool Data
fpm	44	Spline Broach
Diam	1.176	HSS
Depth Cut	3/64	Coolant Cutting Oil
0.003 Per Tooth		Tool Life 500 Pcs
		Per Grind



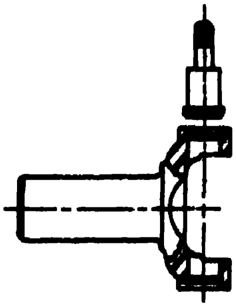
7th Operation

Mach Data		Tool Data
fpm	26.5	Surface Broach
Rougher	0.0043	HSS Broach
Semi Fin	0.0019	Coolant Cutting Oil
Depth Cut	.0048	Tool Life 10000
Per Tooth		Pcs Per Grind



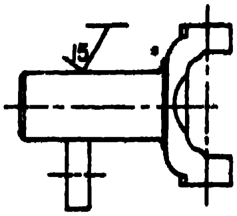
8th Operation

Mach Data		Tool Data
rpm	208	Drill Cross Hole
fpm	340	Std One Inch HSS Drill
fpr	0.011	Coolant Soluble Oil
		Tool Life 165 Pcs
		Per Grind



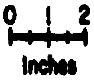
11th Operation

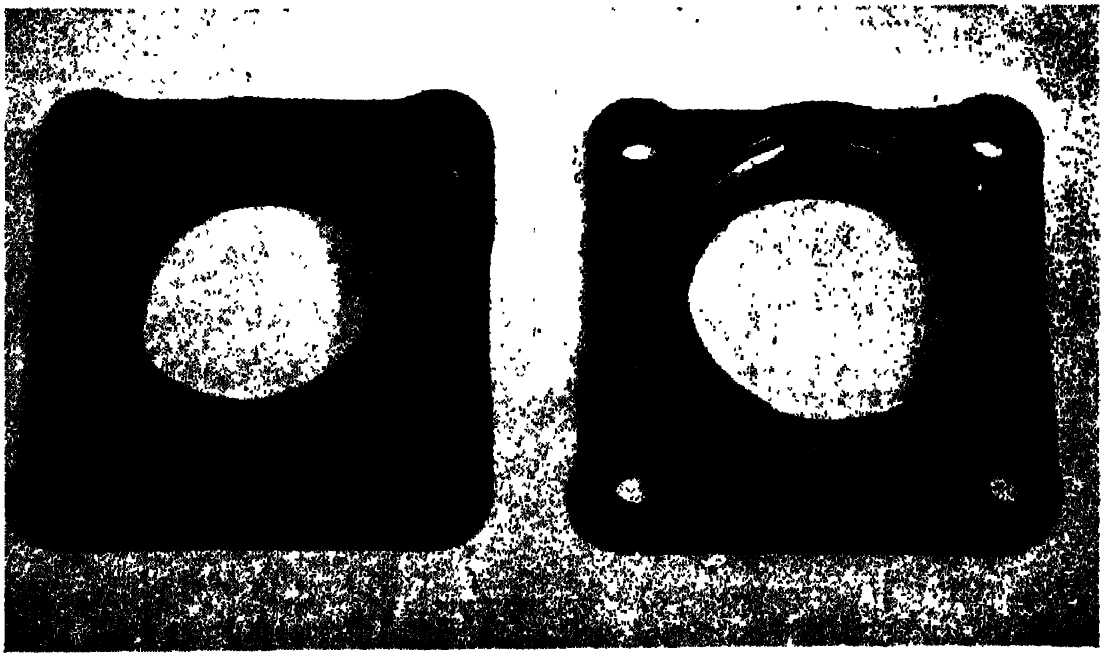
Mach Data		Tool Data
rpm	343	Cut Snap Ring Groove
fpr	0.004	HSS Circular Form
		Tool
		Tool Life 500 Pcs
		Per Grind



12th Operation

Mach Data		Tool Data
Wheel rpm	830	Grind Stem
Work rpm	192	Wheel A 805-
Depth Cut	0.010	N6-V
		Pcs Per Dress 110
		Coolant Detergent
		Economy 1 To 200





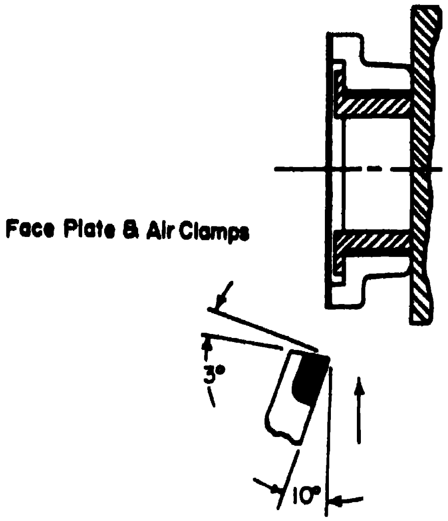
Case History 8

Flange Bearing Housing

This part furnishes a good illustration of a moderately complex series of machining steps. These include end boring, multiple drilling, double end boring, and milling. A total of six operations are performed. Of particular interest is the employment in boring of carbide insert tools at high machining speeds. These are interchangeable, and new cutting edges are readily available since each insert provides a total of eight separate cutters.

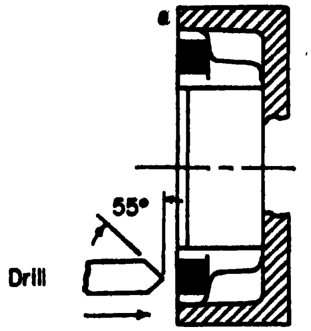
1st Operation

Mach Data		Tool Data
Single End Boring Mach		Turn Flange Face
		Kenna Metal K-21
rpm	296	Tool Life 165 Pcs Per Grind
fpm	465	
fpr	0.010	
Depth Cut	1/16	



2nd Operation

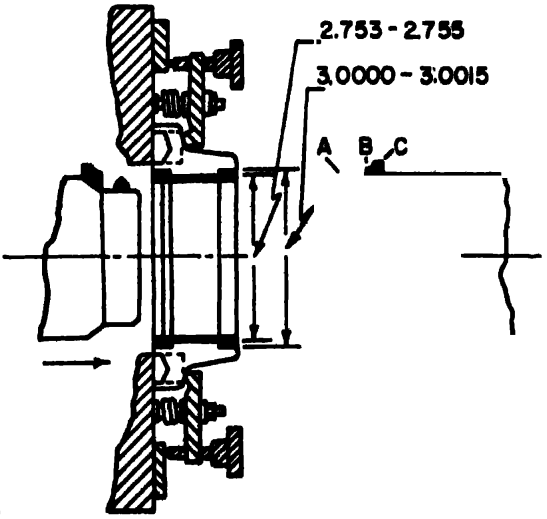
Mach Data		Tool Data
Eight Spindle Drill Press		Drill Four Holes 17/32 Diam Two Parts At A Time
rpm	794	
fpm	105	HSS Drill
fpr	0.003	Tool Life 340 Pcs Per Grind
Four Holes Between Centers 5 1/8		
Depth Cut	9/16	

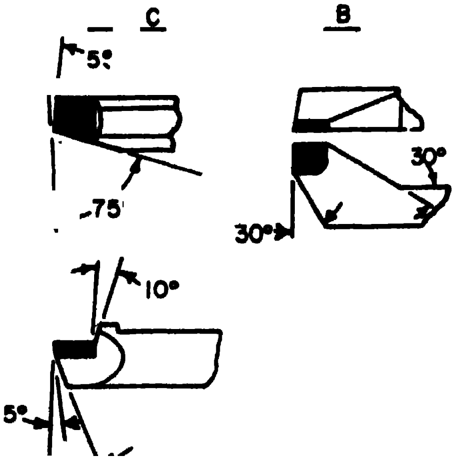


Two Jaw Air Chuck

3rd Operation

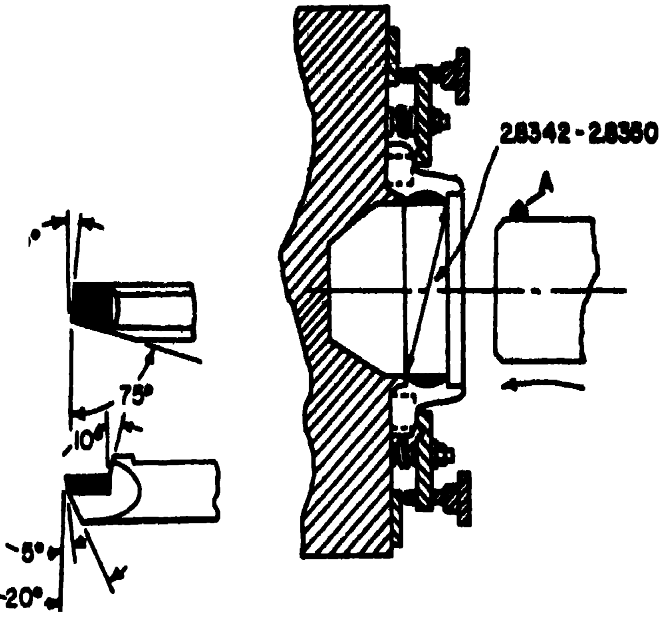
Mach Data		Tool Data
Double End Boring Mach		Turn Bore
		Two Counter Bores & Chamf
rpm	370	
fpm	350	KennaMetal K-21
fpr	0.007	Tool Life 164 Pcs Per Grind





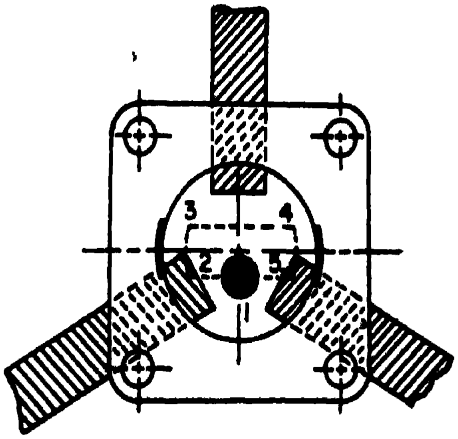
4th Operation

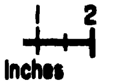
Mach Data		Tool Data
Single End Boring Mach		Turn Spherical Bore
rpm	507	Kenna Metal K4H
fpm	440	Tool Life 160 Pcs Per Grind
fpr	0.006	
Depth Cut	0.040	

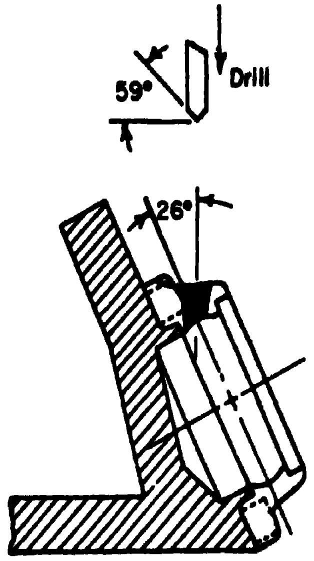


5th Operation

Mach Data		Tool Data
Four Spindle Profile Milling Mach		Mill Entrance Slots HSS End Milling Cutters 5/8 Diam
rpm	630	
fpm	0.015	Tool Life 2000 Pcs Per Grind
Depth Cut	0.061	

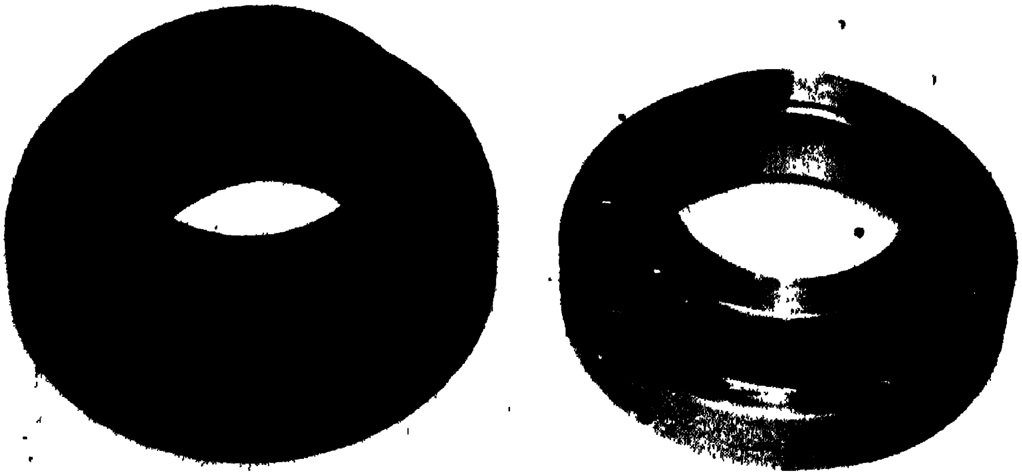






6th Operation

Mach Data		Tool Data
rpm	695	Drill One Hole 21/64 At An Angle Of 26° With The Vertical
fpm	0.009	
Two Spindle Drill Press		1/8 Pipe Tap 1/4 Deep Tool Life 900 Pcs Per Grind



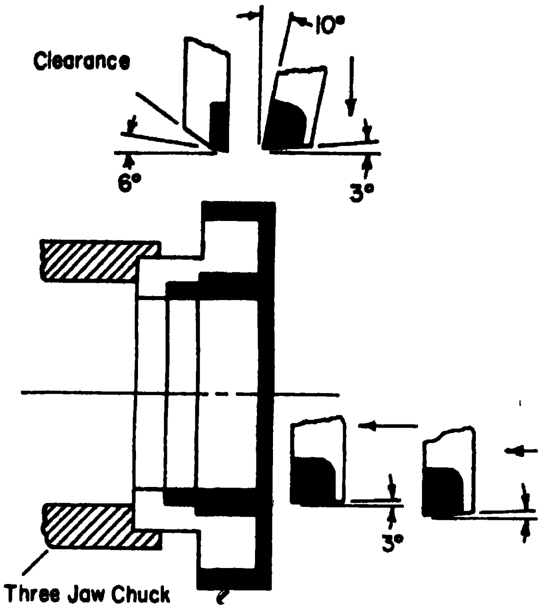
Case History 9

Flexible Gear Coupling, Male Housing

This casting is produced in grade 45010 pearlitic malleable iron in order to gain the advantages of required strength combined with high elongation and machinability. All operations except the last (induction brazing), are multiple and clearly illustrative of the use of carbide tools.

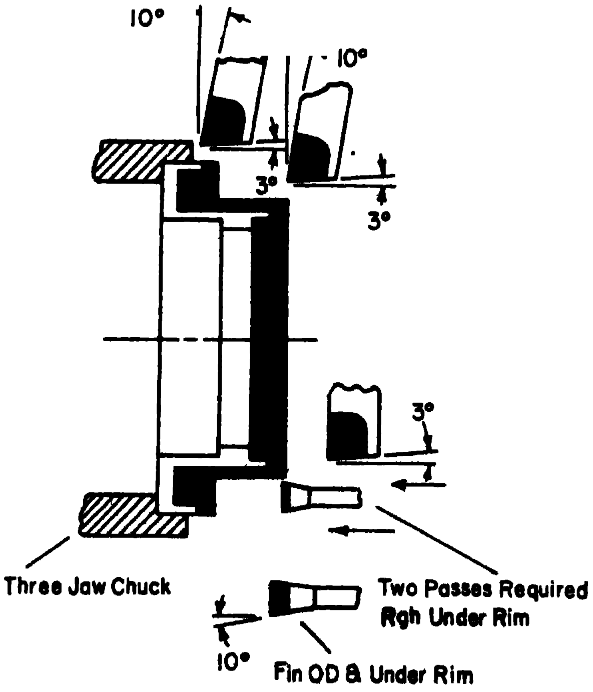
1st Operation

Mach Data		Tool Data
Hand Chucking		Rgh & Fin
Lathe		Turn OD
rpm	184	Carboloy 370
fpm	290	Tool Brazed To Steel
fpr	0.015	Shank
OD	5 15/16	Tool Life 35 Pcs
Depth Cut	1/4	Per Grind
rpm	304	Rgh & Fin
fpm	310	Bore
fpr	0.013	Carboloy 370
ID	3.937	Tool Brazed To Steel
Depth Cut	3/8	Shank
		Tool Life 35 Pcs
		Per Grind
rpm	184	Rgh Face
fpm	290	Carboloy 370
fpr	0.015	Tool Brazed To Steel
Depth Cut	3/16	Shank
		Tool Life 35 Pcs
		Per Grind
rpm	250	Fin Face
fpm	390	Carboloy
fpr	0.015	Tool Brazed To Steel
Depth Cut	0.015	Shank
		Tool Life 35 Pcs
		Per Grind



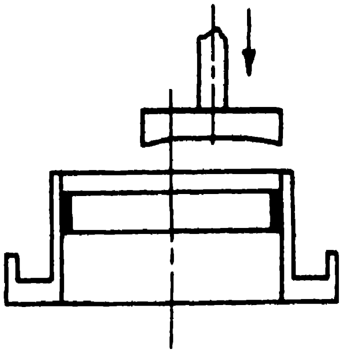
2nd Operation

Mach Data		Tool Data
Hand Chucking		Rgh & Fin
Lathe		Face
rpm	199	Carboloy 370
fpm	312/208	Tool Brazed To Steel
fpr	0.066	Shank
OD	5 15/16	Tool Life 35 Pcs
Depth Cut	1/4	Per Grind
rpm	342	Rgh & Fin
fpm	492/384	Turn
fpr	0.016	Carboloy 370
OD	4 5/16	Tool Brazed To Steel
Depth Cut	1/8	Shank
		Tool Life 35 Pcs
		Per Grind
rpm	304	Rgh Bore
fpm	310	Carboloy 370
fpr	0.013	Tool Brazed To Steel
ID	4	Shank
Depth Cut	3/16	Tool Life 35 Pcs
		Per Grind
rpm	304	Fin Bore
fpm	310	Carboloy 370
fpr	0.006	Tool Brazed To Steel
ID	4	Shank
Depth Cut	0.015	Tool Life 35 Pcs
		Per Grind



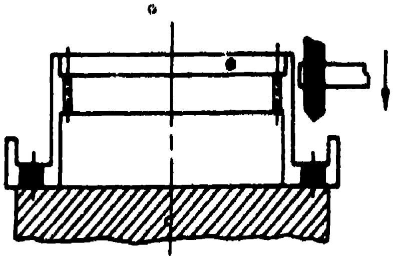
3rd Operation

Mach Data	Tool Data
Vertical Gear Shaper	Cut Internal Gear
rpm 650	Gear Shaper
Strokes Per Revolution Of Mach 1162	Standard HSS Cutter Diametrical Pitch 16 Pressure Angle 20°
ID 3.657 $^{+0.003}_{-0.000}$ Between Two 0.0937 Diam Pins	



4th Operation

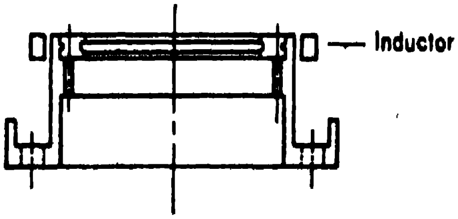
Mach Data	Tool Data
Six Spindle Drill Press	Drill Seven Holes 0.337 Diam 11/32 Deep
rpm 925	
fpm 91	HSS
fpr 0.006	

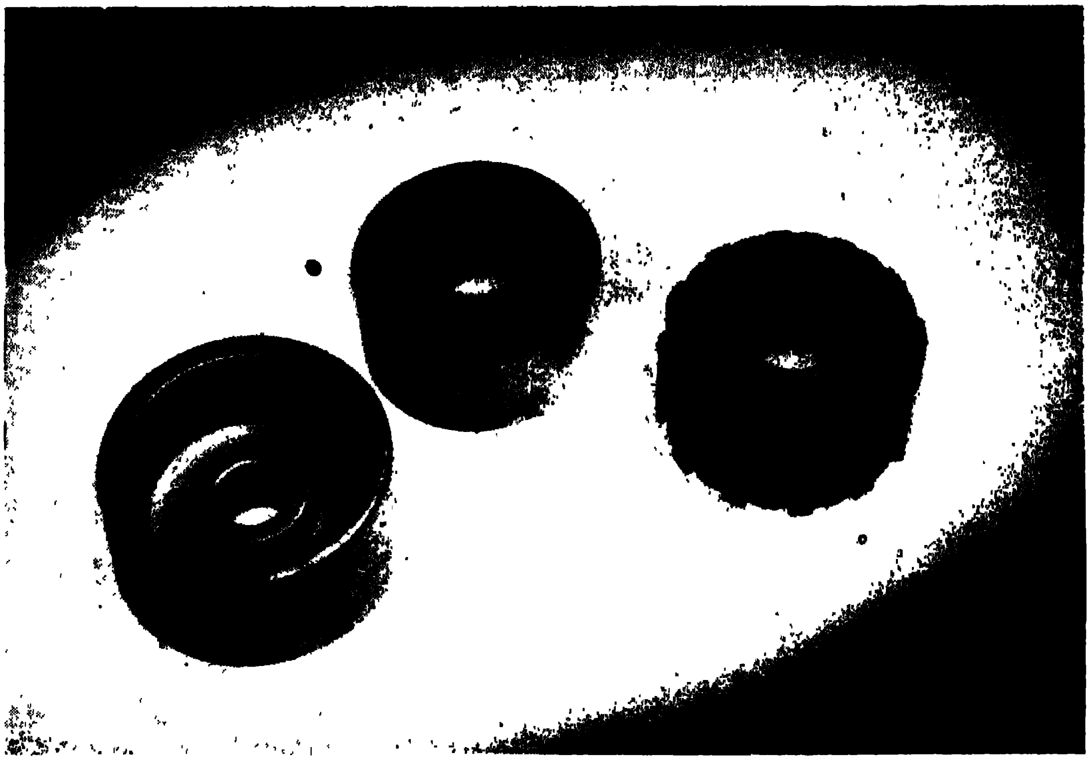


Indexing Fixture

5th Operation

Mach Data	Tool Data
Inductor 80 Kw 10 000 Cycles	Induction Silver Braze End Cap





Case History 10

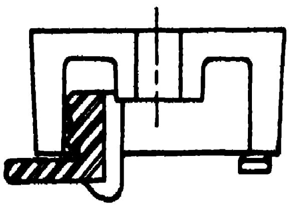
Hub Transmission Direct Clutch

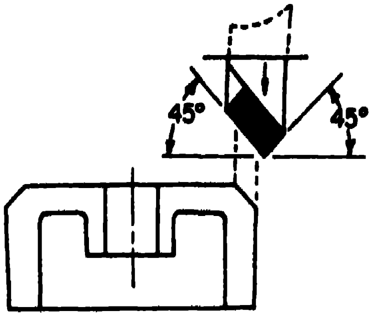
This high-production part for a three-speed automotive transmission replaces an alloy forging at considerable reduction in machining cost. It is now supplied by five different foundries to a maximum demand of 5,000 per day or greater.

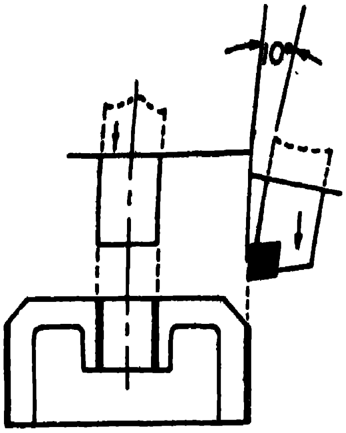
A total of nine sequences is required in the finishing. Some of these are multiple operations involving as many as fifteen stations performing nineteen distinct functions. Practically every operation known to the field of machining is carried out on this part. This makes it an unusually good example of modern practice with both carbide inserts or high speed steel tools.

The original casting weighing 3½ lbs. becomes the part shown in the photograph at 1.0 lb. The final step of induction hardening is an outstanding example of the excellent hardenability of malleable iron. This is carried out simultaneously on three parts with an automatic indexing fixture, one tooth at a time. The part, as installed, outwears the original forging, which it replaced; it is lighter in weight and requires the removal of much less metal with greater ease of machining.

First Chucking







1st Station

Loading

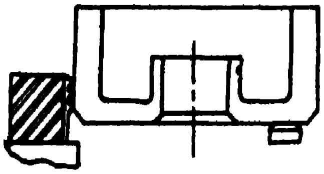
2nd Station

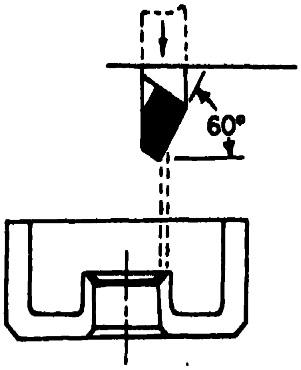
Mach Data	Tool Data
rpm 288	Chamf OD
fpm 300	Carboloy 78
fpr 0.0150	Rake 0°
Cycle 0.17	Chipbreaker
Depth Cut	Tool Life
3/32	600 Pcs

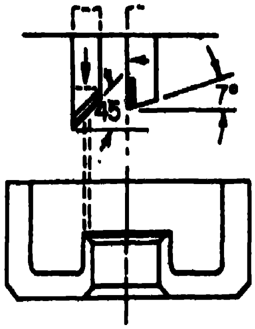
3rd Station

Mach Data	Tool Data
rpm 288	Rgh Bore ID
fpm 83	HSS Std Core
fpr 0.0167	Tool-Life
Cycle 0.33	600 Pcs
rpm 288	Rgh Turn OD
fpm 315	Carboloy 370
fpr 0.0167	Neg Rake 7°-7°
Cycle 0.33	80° Insert
Depth Cut	Tool Life
3/32	600 Pcs

Second Chucking







1st Station

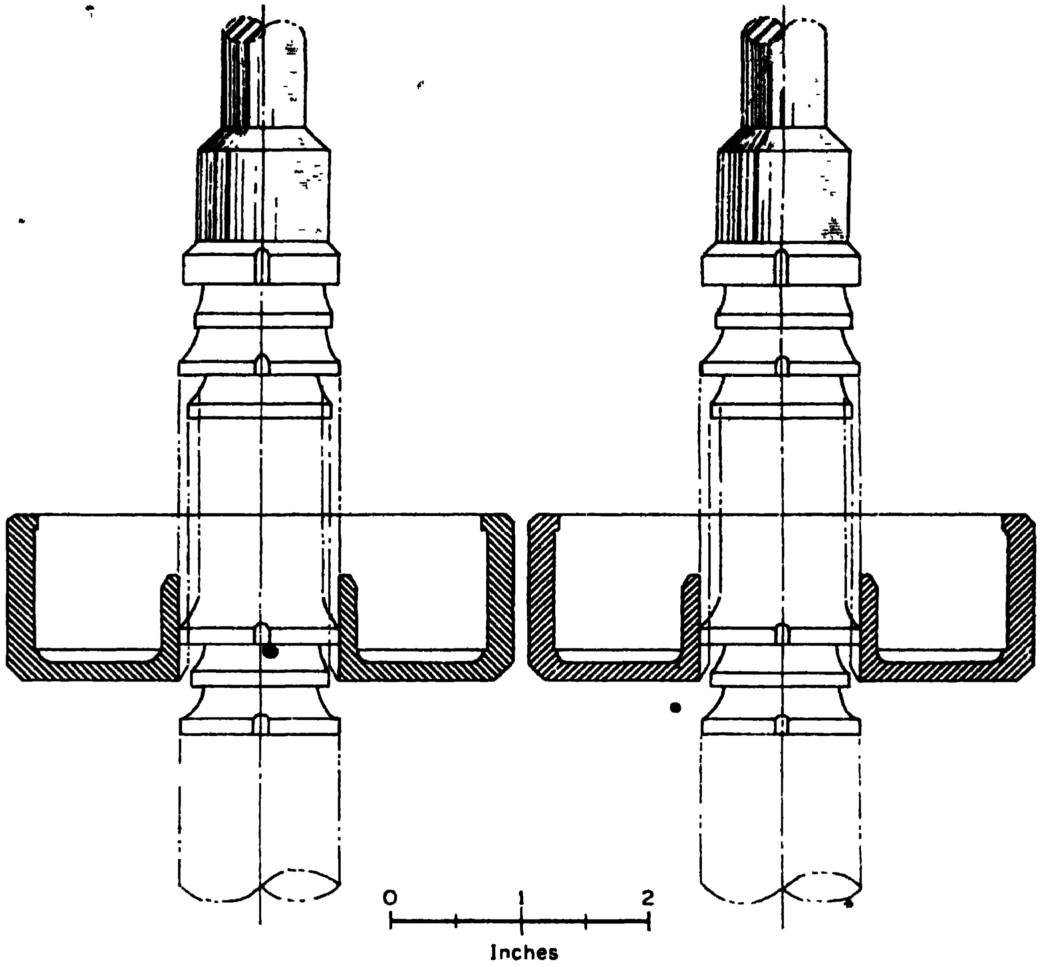
Loading

2nd Station

Mach Data	Tool Data
rpm 288	Chamf ID Bore
fpm 90	Carboloy 370
fpr 0.0150	Top Rake 5°
Cycle 0.17	Tool Life
Depth Cut	600 Pcs
3/32	

3rd Station

Mach Data	Tool Data
rpm 288	Fin Face Hub
fpm 91	Carboloy 78
fpr 0.0167	Tool Life
Cycle 0.33	600 Pcs
Depth Cut	Fin Chamf Hub
3/32	Carboloy 370
	Tool Life
	600 Pcs



Second Operation

Mach. Data	Tool Data
Two Station Broaching Mach	Broach 24 Internal Splines Two Parts at A Time
Production 234 Pcs Per Hr	Coolant High Pressure Cutting Oil
	Tool Life 3500 Pcs Per Grind

Third Operation

Wash

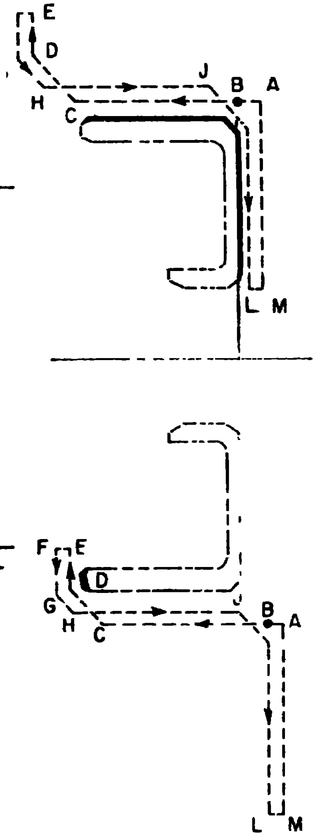
Machine – Conveyor Type Washer
Solution – Alkaline Cleaner, Cold

Mach Data

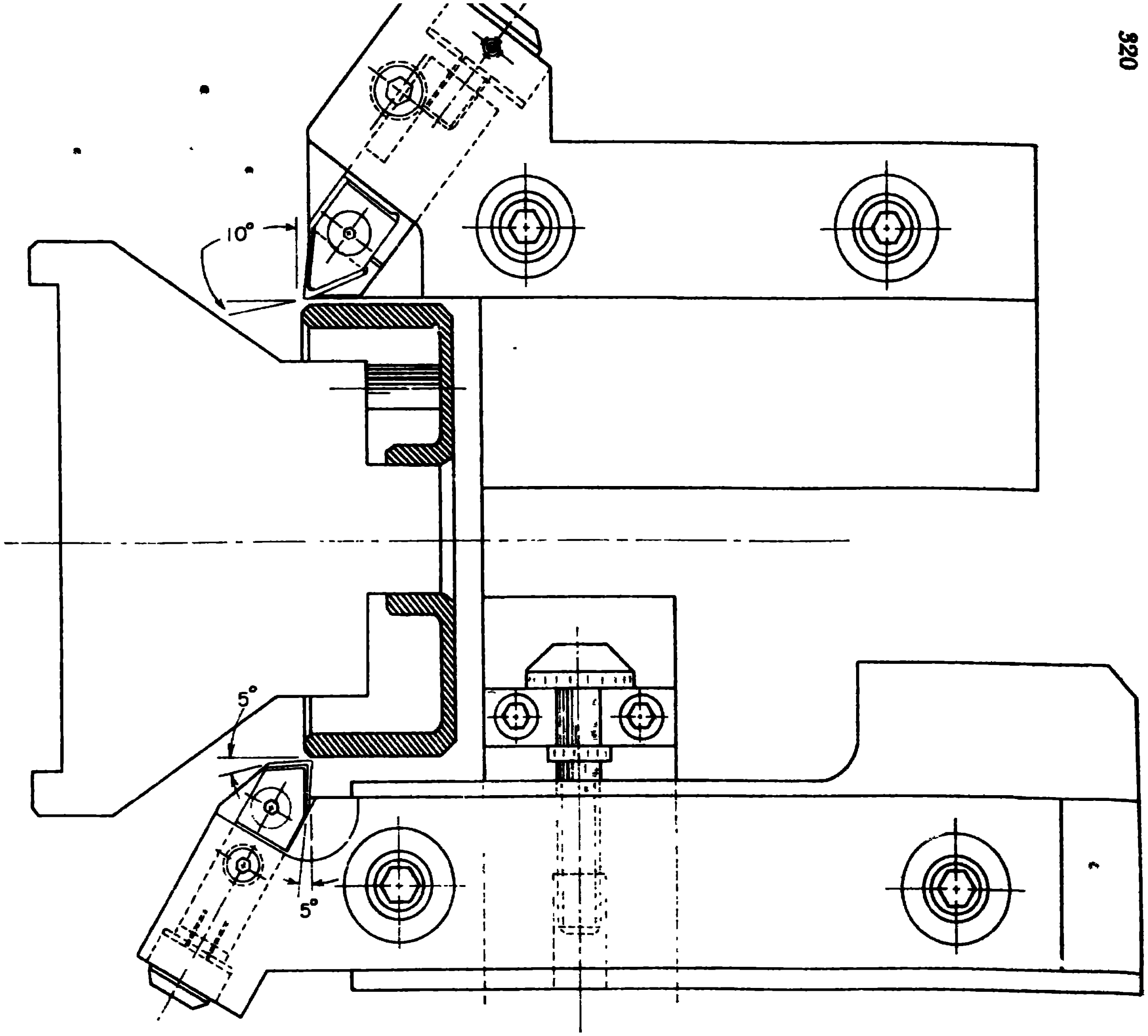
al Head Cam Type Automatic
Tracing Lathe
m 782
m O.D 800
r 0.012 O.D and Face
ıpth of Cut O.D. 0.012
oduction 266 Parts Per Hr

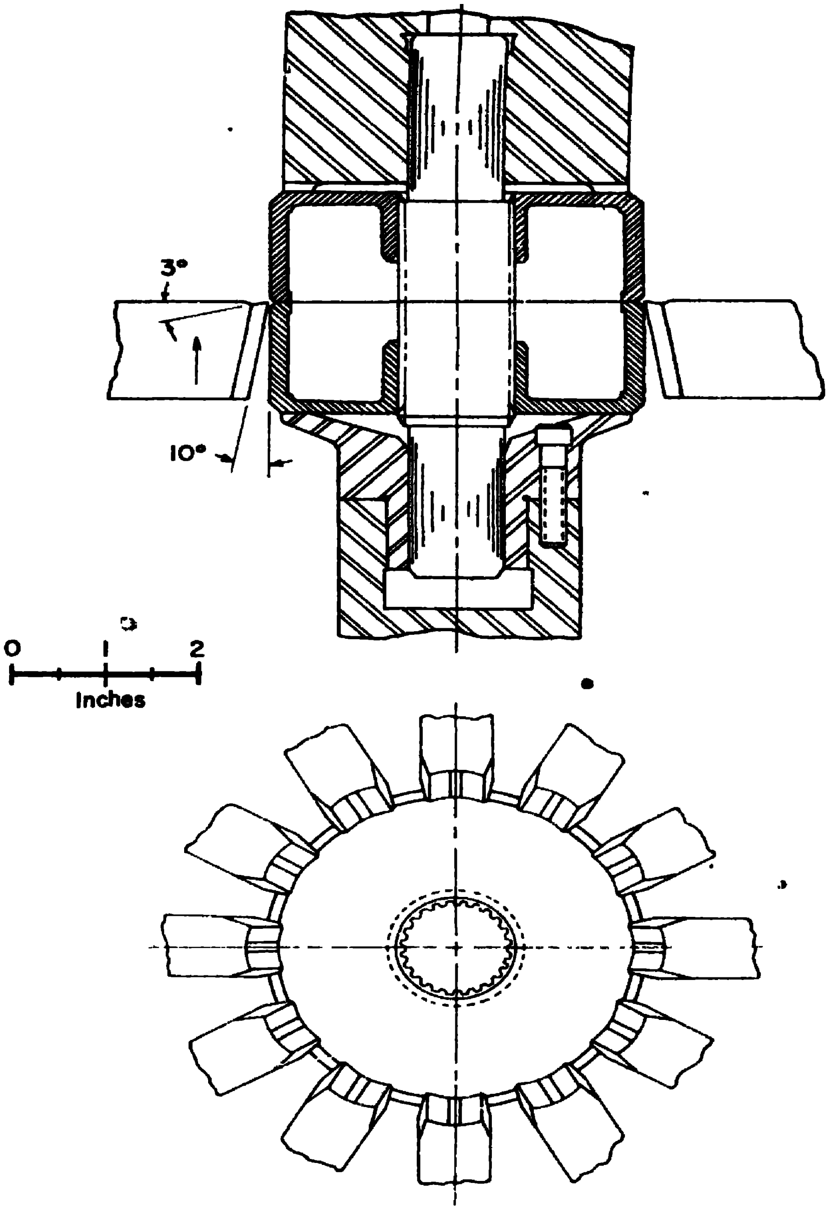
Tool Data

n. Turn O.D. - Face Closed End-
Chamf.
olid 3/8 Triangle Oxide
ol Life - 160 Pcs.
ıce Open End - Chamf.
ırboloy 883
ool Life 600 Pcs

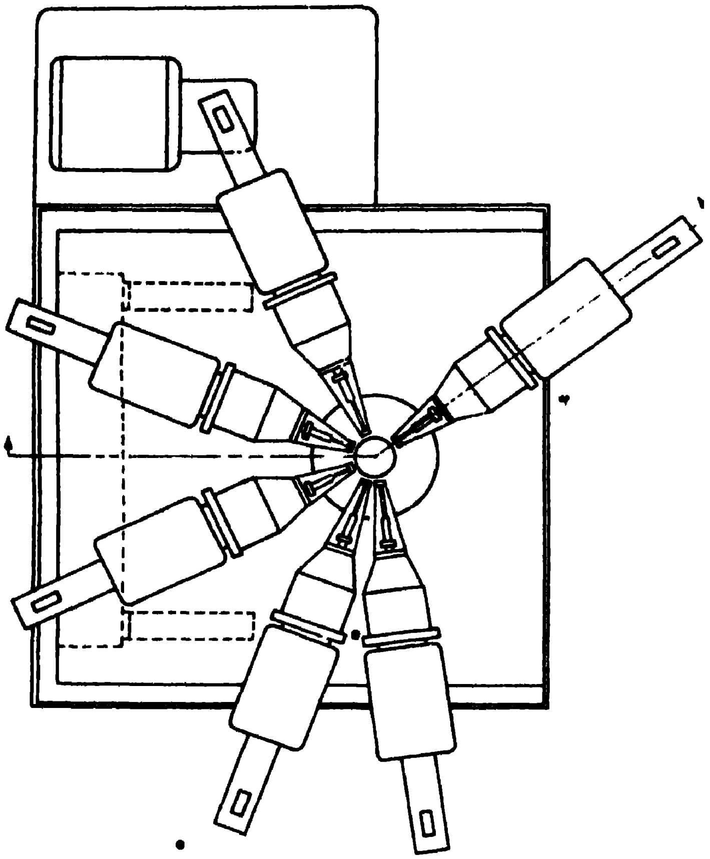


TOOL PATH





Mach Data	Tool Data
Twelve Blade Slotting Machine	Twelve HSS Per Set
Production 140 Pcs Per Hr	Coolant High Pressure Cutting Oil
	Tool Life 750 Pcs Per Grind



Sixth Operation

Wash

Machine	Conveyor Type Washer
Solution	Alkaline Cleaner Warm 120°F

Seventh Operation

Drill Twelve 3/16 Diam Holes

Mach Data

Multiple Spindle Drill

Production 183 Pcs Per Hr

Tool Data

Drill Six 3/16 Diam Holes, Index, Drill Six Additional Holes

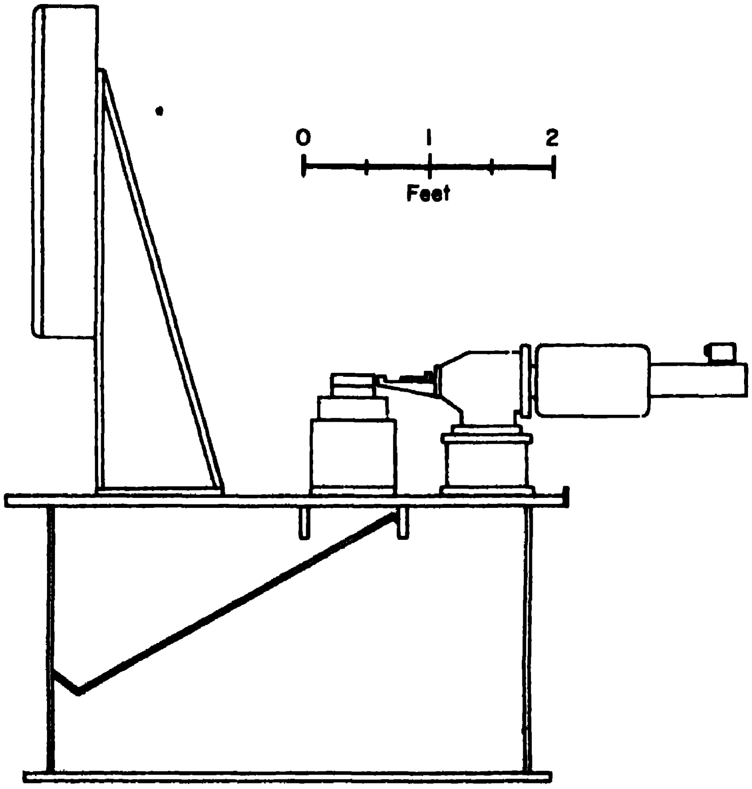
rpm 1730

Coolant Soluble Cutting Oil 20-1

Tool Life 1500 Holes Per Grind

Eigth Operation

Roto Finish



XI

THE METALLURGY OF MALLEABLE IRON

ALL IRONS and steels are iron-carbon alloys, made up of varying proportions of substantially the same group of elements, which pass through various metallurgical changes in the process of manufacture. The properties which give malleable iron its great range of usefulness in industrial applications are functions primarily of the chemical composition of the melt and the metallurgical form in which the components are fixed by that chemistry and by the manufacturing procedures used. This chapter hence will discuss, in turn, pure iron, since it is the basis of all ferrous alloys; the influence of carbon and other elements that are essential to the manufacture of malleable iron; the effect of the malleableizing heat treatment on the chemistry and metallurgical structure of the initial white iron casting; and the similarities and differences in these matters between standard and pearlitic malleable irons.

PURE IRON

The existence of other elements in iron may exert a profound influence on the properties of the material. In discussing the metallurgy of malleable iron, therefore, it seems proper first to give some cursory consideration to the "pure" irons that may be produced by present-day methods.

Absolutely uncontaminated iron has not yet been produced in commercial quantities. For laboratory evaluations of the properties of iron, small batches have been made (e.g. electrolytic, carbonyl, N.B.S., and Kahlbaum irons,[152,153,154]) containing total impurities of the order of 0.02 per cent by weight or less. Iron oxide of high purity can be reduced in heated thoria crucibles in a current of dry hydrogen to give 99.95 per cent pure iron. Some success has been reported[155,156] wherein Swedish pig iron has been induction melted in a closed chamber and refined under successive oxidation, vacuum, and reduction (hydrogen) treatments. Through spontaneous crystal growth, whiskers of pure iron 2 inches long and only 0.001 inch thick have been produced; these were found to have a strength equal to one million pounds per square inch.[207] Still smaller crystals, only 4 x 10^{-9} inch in cross-section, made by a somewhat different technique, exhibited tensile strength of 1,900,000 p.s.i., or close to the theoretical maximum.[208,265]

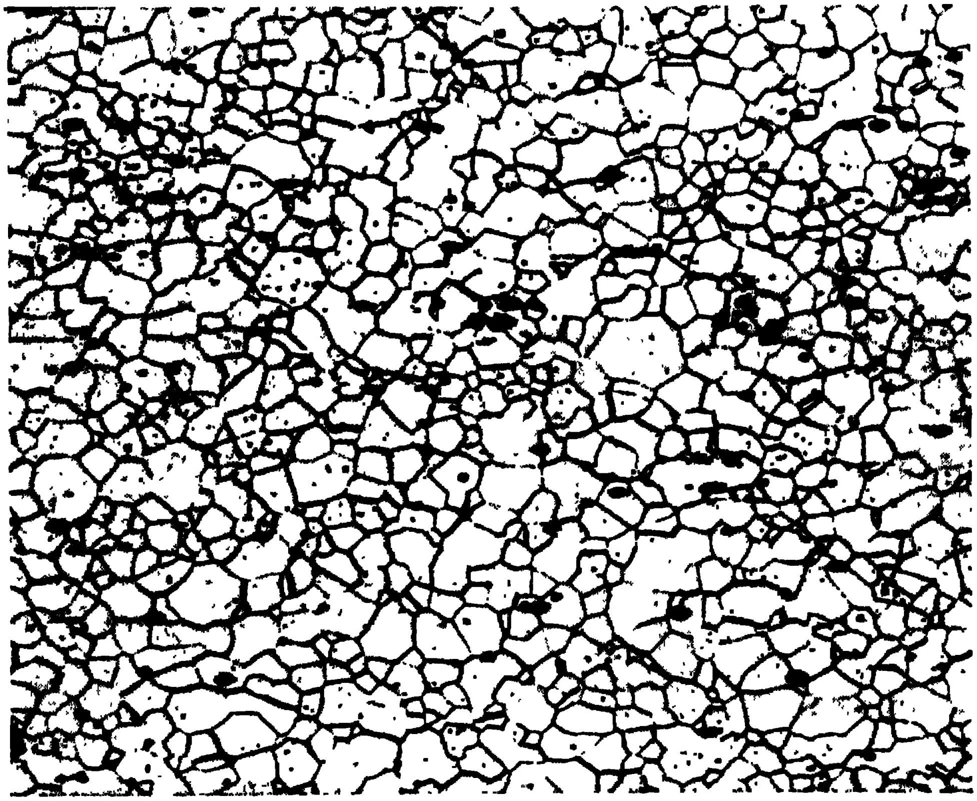


Fig. 1. Commercially pure iron: "Armco" ingot iron that has been normalized, grain size is ASTM No. 7. The etchant used was a 3% nital solution (3% nitric acid, 97% absolute methyl alcohol), magnification 100 ×.

Commercially produced iron of low impurity content is known as Armco, or ingot iron (Fig. 1). It contains about 0.1 per cent total contaminants. It is essentially a mild steel which is highly refined by the basic open hearth process and is subsequently worked into desired shape by forging. One other product of commercial significance is wrought iron (Fig. 2), which contains up to 250,000 threads of iron silicate slag per square inch of cross-section. Although this slag will average around 3 per cent of the weight of wrought iron, the balance of the material, the iron matrix itself, has only about 0.25 per cent total dissolved contaminants. The fibrous slag arises from working a hot pasty bloom of wrought iron in one direction.

In addition to possessing the properties listed in Table 1, pure iron is soft, malleable, and ductile. When finely divided it is pyrophoric; that is, it will ignite spontaneously when heated in air. Iron will take a good

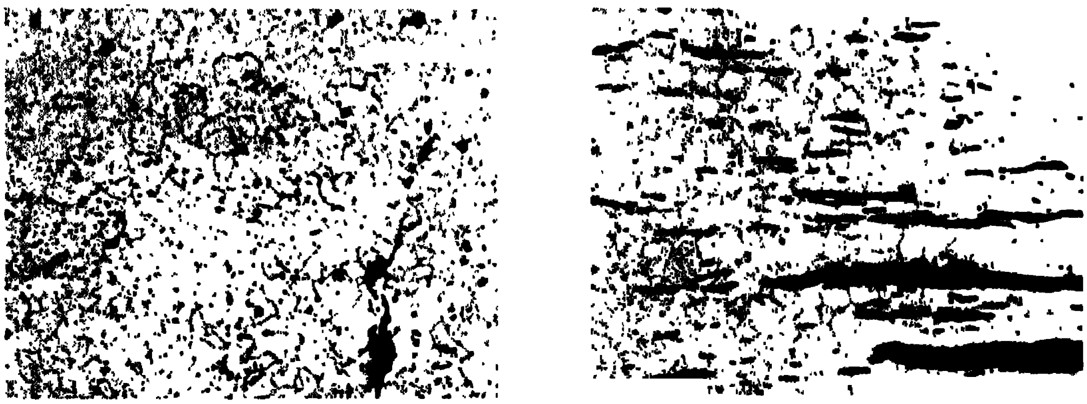


Fig. 2. Transverse (left) and longitudinal (right) sections of wrought iron. The dark inclusions are slag stringers. 3% nital, magnification 100 X.

TABLE 1. CONSTANTS FOR PURE IRON

Density: 7.874 gm./cu. cm. at 20 degrees C.
0.284 lbs./cu. in. at 20 degrees C.

Specific Heat: 0.107 cal./gm./degrees C. at 20 degrees

Atomic Number: 26

Atomic Weight: 55.85

Heat of Fusion: 65 cal./gm.; 117 BTU/lb.

Melting Point: 2800 degrees F.

Boiling Point: 4960 degrees F.

Thermal Conductivity: 0.18 cal./sec./cm.^{2}/degrees C./cm. at room temperature
.16 " " " " " " at 200 degrees F.
.11 " " " " " at 400 degrees F.
.07 " " " " " " at 800 degrees F.

Coefficient of Linear Expansion:

Coefficient x 10^{-6} (Increase in length per unit length per degree C.)	*Temperature (°C)*	*Temperature (°F)*
11.7	0	32
12.7	100	212
14.8	300	572
16.0	600	1112

Electrical Resistivity: 9.71 microhm-cm. at 20 degrees C.

Young's Modulus (in tension): 27,200,000 to 30,000,000 p.s.i.

Poisson's Ratio: 0.28

Hardness: 97-105 Brinell Hardness Number

Tensile Properties: (at room temperature), commercially pure iron.

Tensile Strength:	42,000-48,000 p.s.i.[*]
Yield Strength:	18,000-32,000 p.s.i.
Elongation:	42-48 per cent in 2 inches
Reduction in Area:	65-78 per cent

[*] **1,900,000 p.s.i. tensile strength in tiny, pure iron whisker.**

luster when polished. When it is heated to 400-600 degrees F. in air or in steam, a thin compact iron oxide film forms on the surface, imparting a "temper" color that ranges from brown (gamma Fe_2O_3) at the lower temperature to bluish (probably Fe_3O_4) at the higher temperature. This oxide skin is somewhat protective to the iron against atmospheric corrosion. If, however, the metal is heated to higher temperatures (e.g. 1100 degrees F. and above) the scale will consist mostly of FeO[266] and is loose and easily removable.[266] At still higher temperatures in air, a scale forms which is ferric oxide, Fe_2O_3, on the outside and graduates to a more complex oxide in the layers within. Particularly above 1650 degrees F., oxidation initially attacks the grain boundaries on the surface layers, tending to weaken the strength and decrease the ductility of the iron.

Iron of extremely high purity is not appreciably attacked by water containing dissolved oxygen or carbon dioxide, but commercially "pure" iron has sufficient traces of impurities to permit ferric hydroxide, or "rust," to form on the surface when it is exposed to moist air. As this rust is neither closely adherent to the iron nor impervious to water, the attack usually progresses at an accelerated velocity. Dilute mineral acids react readily with commercially pure iron, but passive resistance is offered against most alkalis.

TEMPERATURE EFFECTS ON "PURE" IRON

Depending upon the temperature, high-purity iron exists in six different states, each of which differs from the others in structure or properties or both. A consideration of these varieties of iron that exist at each of the six-temperature ranges is in order.

TEMPERATURE RANGE I: BELOW 1414 DEGREES FAHRENHEIT

"Pure" iron, up to 1414 degrees F., is ferromagnetic, that is, strongly magnetic; it is called alpha (α) iron. Crystallographically it may be pictured as consisting of countless minute tridimensional structural blocks,

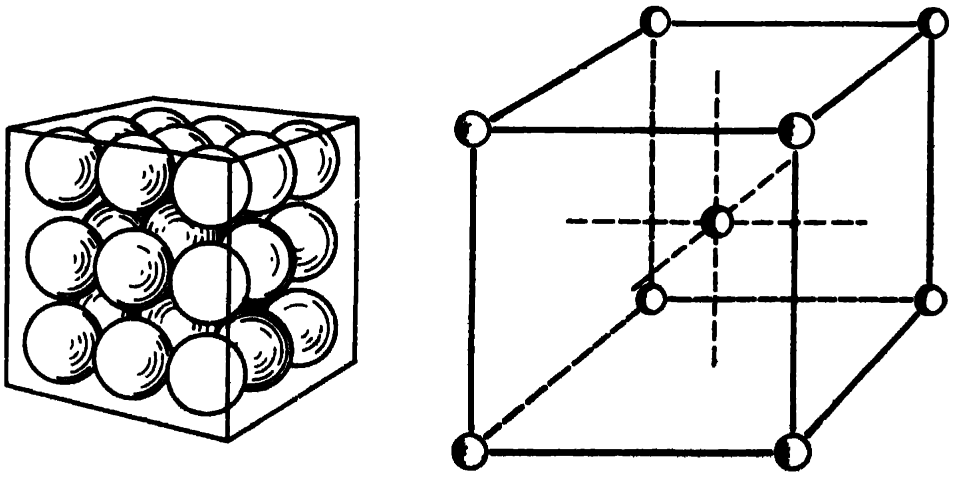


Fig. 3. **Idealized arrangement of body-centered cubic packing. This arrangement of atoms in the crystal lattice is representative of the crystalline form of alpha and delta iron.**

all of which are identical in arrangement and in orientation to one another. These unit cells of iron at room temperature have three axes of equal length (2.8664 Angstroms) which are perpendicular to each other. The structural lattice of iron is therefore cubical in shape. There are iron atoms at the eight corner positions of the cube, plus one additional iron atom at the geometric center of the cube. Hence the lattice is designated as body-centered cubic, as is shown in Fig. 3.

Some of the properties of pure iron show a reversal at temperatures ranging from 70 to 400 degrees F. This change depends upon testing speeds, occurring at higher temperatures with faster speeds. Short-time test results are summarized in Table 2. The modulus of elasticity in tension shows a continuous decline with increasing temperatures. For example a modulus of 29,800,000 p.s.i. at room temperature will drop to around 24,000,000 p.s.i. at 800 degrees F.

TABLE 2. MECHANICAL PROPERTIES OF PURE IRON AT ELEVATED TEMPERATURES

Temperature, °F.	60	400	842	1100	1300
Tensile Strength, p.s.i.	49,500	65,600	37,000	15,200	9,200
Youngs' Modulus x 10^6, p.s.i.	29.8	27.8	24.0	..	..
Elongation, per cent:	45	27	51	34	54
Reduction Area, per cent:	69	54	68	50	56
Brinell Hardness Number:	105	140	50	..	..

The specific heat of alpha iron increases in this temperature range from 0.104 to 0.320 cal./gm./degree C. The heat content varies correspondingly from about 15 to 210 B.T.U. from the bottom to the top of the temperature range. Table 1 indicates changes that take place in the thermal conductivity and coefficient of linear expansion with temperature changes.

TEMPERATURE RANGE II: 1414 TO 1660 DEGREES FAHRENHEIT

While iron in this range does not transform structurally, it does become paramagnetic; i.e., practically non-magnetic. The temperature at which this change from magnetic to paramagnetic alpha (α) iron occurs is known as the Curie point, or the A_2 transformation temperature. Within this range the specific heat reverses the trend shown in magnetic alpha iron and decreases from 0.32 cal./gm./degrees C. to 0.16 cal./gm./degrees C. as the upper end of the range is approached.

TEMPERATURE RANGE III: 1660 TO 2530 DEGREES FAHRENHEIT

If iron in temperature range II is further heated at a constant rate of input, it will be found that at a certain temperature (the A_3), about 1670 degrees F., the steady rise in temperature suddenly levels off for a while before resuming its increase again (although now at a somewhat different rate). The reason for the temporary arrest is that a structural, or polymorphic, transformation is taking place that requires thermal energy

(3.63 calories per gram). On the basis of X-ray analysis it can be verified that this change has involved a reorganization of the crystallographic lattice which, though still in the cubic system, has one iron atom in the center of each of the six faces of the cube, in addition to the eight atoms at corner positions. There is no longer an atom at the cube's center Because of this arrangement, the system is called face-centered cubic; it is presented diagrammatically in Fig. 4. The length (parameter) of each side of the new cubic lattice is about 26 per cent greater than that of the body-centered cube of alpha iron, representing a parameter increase from 2.90 to 3.65 kX.

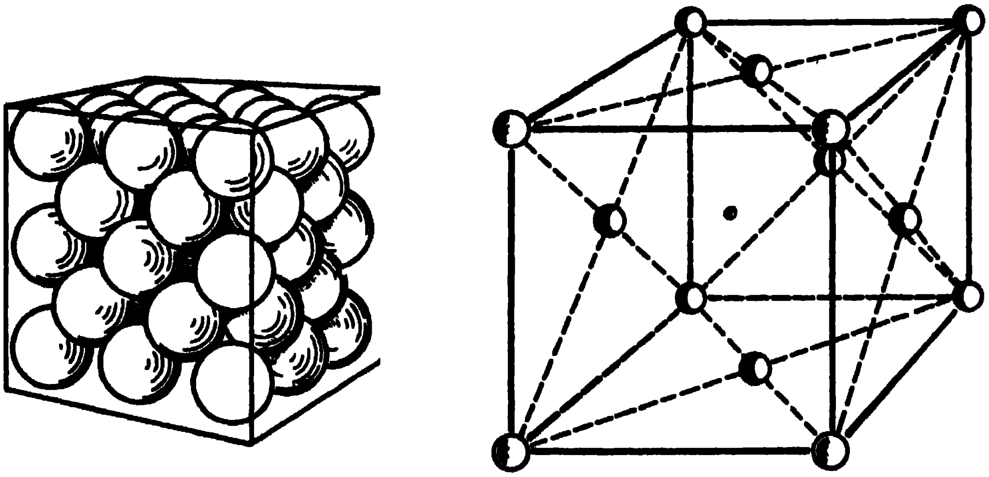


Fig. 4. Idealized arrangement of face-centered cubic packing. This arrangement of atoms in the crystal lattice is representative of the crystalline form of gamma iron.

This new allotropic form is called gamma (γ) iron. Like α iron, it too is paramagnetic. If gamma iron is cooled slowly, transformation back into the body-centered cubic form will take place at about 1656 degrees F. (the Ar_3) with generation of the heat of transformation. It will be noted that this change occurs at a somewhat lower temperature on cooling than it does on heating. Hence the two designations Ac_3 (heating) and Ar_3 (cooling) are employed to indicate the transformation $\alpha \rightleftharpoons \gamma$, depending upon whether the temperature is going upward or downward. Rapid rates of heating or cooling will displace the transformation temperature to a greater degree than will slow rates.

Specific heat shows only a slight, gradual increase in temperature range III (from 0.161 to 0.169 cal./gm./degrees C). The thermal conductivity of gamma iron appears to increase with an increase in temperature, which is a reversal of the trend of alpha iron.

Temperature Range IV: 2530 to 2800 Degrees Fahrenheit

When iron is heated beyond the range in which it exists as gamma iron (i.e. above 2530 degrees F., the A_4 temperature), the face-centered cubic lattice will again return to the body-centered cubic system, which apparently is identical in crystalline form with alpha iron. The heat absorbed in the transformation is 1.7 cal./gm.

The new phase is delta (δ) iron. Since its properties follow the trend initiated in alpha iron, which was interrupted by the gamma phase, δ is often regarded as an extension of the alpha phase at high temperatures. Thus the rate of thermal expansion follows the same linear relation to temperature as was found in alpha iron. Delta iron is likewise ferro magnetic.

TEMPERATURE RANGE V: 2800 TO 5430 DEGREES FAHRENHEIT

Delta iron is the highest temperature phase in which iron can exist in the solid state; heating to about 2800 degrees F. will cause the pure metal to melt. That is, after absorbing some 65 cal./gm. at the melting point (viz. the heat of fusion) it will become liquid. This temperature increase results in greater fluidity and, as the top of the range is approached, the vapor pressure rises rapidly. It equals one mm. of mercury at 3450 degrees F., 10 mm. at about 4000, and 300 mm. at 5200 degrees F.

TEMPERATURE RANGE VI: ABOVE 5430 DEGREES FAHRENHEIT

When the vapor pressure of molten iron equals that of the atmosphere, the boiling point has been reached; hence at temperatures over about 5430 degrees F. iron exists in the vapor state.

If pure iron is slowly cooled to room temperature from, say, 6000 degrees F., the resulting cooling curve will be similar to that presented in Fig. 5, on which are indicated the various phases covered in the foregoing discussion.

EFFECT OF CARBON ADDITIONS TO IRON

As was mentioned at the outset of this chapter, the introduction of other elements into iron may produce a marked effect on the properties of the resulting alloyed material. Examining the influence of various elements, excluding the gases, when added to "pure" iron, shows that carbon has the greatest over-all effect. It may therefore seem fitting to study iron-carbon alloys over the complete range of compositions varying from 100 per cent pure iron and no carbon to 100 per cent pure carbon and no iron. Such an investigation would reveal, however, that iron-carbon alloys containing 6.7 per cent or more carbon are so hard and brittle as to have no practical significance in the casting industry, because of the formation at 6.7 per cent carbon of a compound that is Fe_3C and is called iron carbide or cementite. Further discussion therefore will concern only those alloys containing less than 6.7 per cent carbon.

Carbon decreases the coefficient of linear expansion at room temperature from 11.7×10^{-6}/degrees C. at 0 per cent carbon to 8.6×10^{-6} at 3.66 per cent carbon. The fluidity of molten iron is improved by carbon additions; rather slightly up to about 0.9 per cent carbon, but more notice-

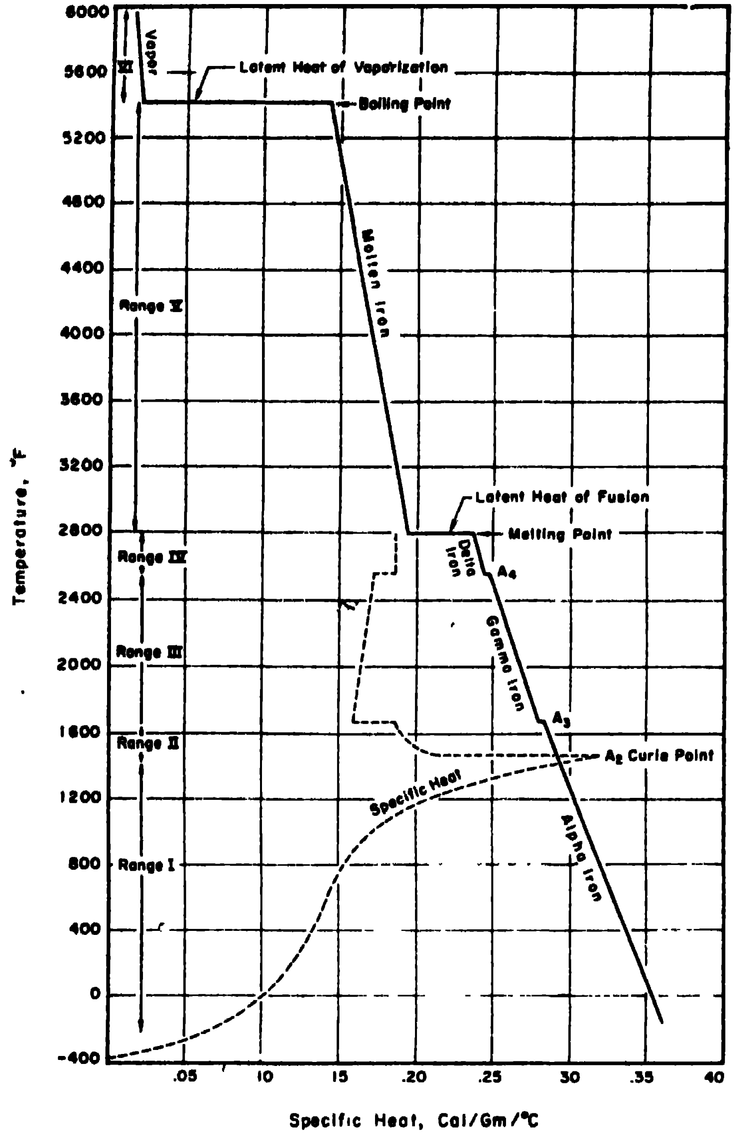


Fig. 5. Specific heat and cooling curves for pure iron.

ably at the higher carbon contents, up to 4.3 per cent. Further carbon additions tend to reduce fluidity. In the low range, carbon increases hardenability for any given grain size. High-carbon irons in which the carbon exists mainly as graphite have excellent damping capacity.

Carbon additions up to 4.3 per cent lower the melting point from 2800 to 2070 degrees F.; further additions raise the melting point. As the melting point is at a minimum for all iron-carbon combinations at 4.3 per cent carbon, this is known as the eutectic composition, and 2070 degrees F. is the eutectic temperature.

Just as water is able to retain dissolved salt or sugar, solidified iron can hold in "solid solution" certain amounts of carbon depending upon the temperature at which the iron-carbon alloy is held. At room temperatures only a trace (0.006 per cent) of carbon can be kept in solid solution. As the temperature is raised to 1333 degrees F., the solubility of carbon in alpha iron (ferrite) is increased only slightly to 0.025 per cent maximum. At higher temperatures wherein gamma iron exists, however, carbon is more readily dissolved, and at 2070 degrees F. up to nearly 2 per cent carbon can be retained in solid solution. Such a solution of carbon in gamma iron is called "austenite." Crystallographic analysis reveals that the carbon atoms in austenite have merely taken up random interstitial positions in the iron lattice, leaving the iron atoms undisturbed in their normal face and corner locations. The greater solubility of carbon in gamma iron may be rationalized on the basis that there is much more room in the interstitial spaces between the iron atoms in the face-centered cubic system than there is in the body-centered cubic ferrite.

In order to visualize more clearly the changes that occur in iron-carbon alloys at various temperatures, it is common practice to conduct

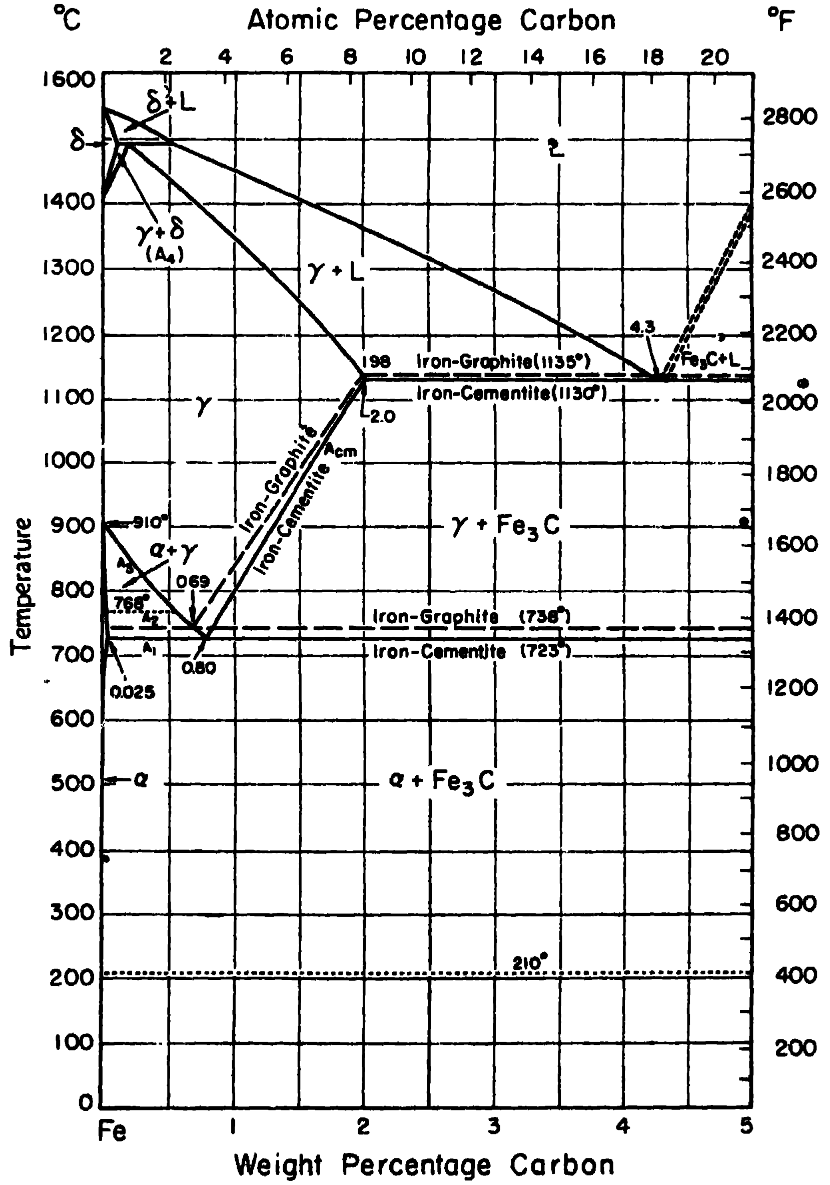


Fig. 6. **A portion of the iron-carbon constitutional diagram.**

thermal analyses of a complete series of irons containing from 0 to 6.7 per cent (by weight) carbon. For example, through inserting thermocouples in a series of molten irons of controlled compositions and permitting the heat to dissipate from the melt slowly and uniformly, the location of phase transformations for each alloy can be determined from the temperature at which thermal arrests occur. These are of the same nature as was found in the cooling curve of pure iron (Fig. 5).

If the points that indicate phase changes for all iron-carbon alloys are combined into one graph plotting temperature vs. composition, the result will be the iron-carbon constitution diagram, which is shown in Fig. 6. The location of the lines in the plot that represent phase changes can be verified by such means as magnetrometric, dilatometric, and metallographic analysis.

The phase that any given alloy will have at a specific temperature can easily be ascertained from the constitution diagram. For example, an alloy of 0.5 per cent carbon would be wholly austenitic between 2600 and 1450 degrees F., and would consist of ferrite and cementite from about 1330 degrees F. down to room temperature. On the other hand, an alloy of 3 per cent carbon would be completely in the molten condition down to about 2300 degrees F., would be solidifying between 2300 and 2066 degrees F., would be composed of austenite and cementite between 2066 and 1333 degrees F., and would consist of ferrite and cementite below 1333 degrees F.

It will be noted that, according to the diagram, austenite does not exist in binary iron-carbon alloys at temperatures below the eutectoid or A_1 temperature, or about 1333 degrees F. When an iron containing austenite is cooled very slowly through this temperature, the austenite transforms into alternate layers, or lamellae, of ferrite and cementite. This structure is called lamellar or laminar pearlite, or merely pearlite, and contains about 0.8 per cent carbon by weight (cf. Fig. 7). The transformation is not instantaneous; rather is takes place by a process of nucleation and growth that originates most commonly at the austenite grain boundaries. Thus, if the rate of cooling is quite high, the formation of pearlite is delayed, taking place at a somewhat lower temperature as a result of this undercooling. A high rate of heating (i.e., superheating) will cause an upward displacement of the transformation temperature. Supercooling and superheating can likewise shift the location of other phase changes downward or upward to some extent, including the upper (liquidus) and lower (solidus) boundaries of the semi-liquid state.

Since pearlite is a mechanical combination of ferrite (a soft, tough phase having 38,000-85,000 p.s.i. tensile strength)[228] and cementite (a hard, brittle constituent with over 200,000 p.s.i. tensile strength), its properties would be expected to be a blend of the two, as they are. Lamellar pearlite has tensile strengths ranging from 120,000 p.s.i. to

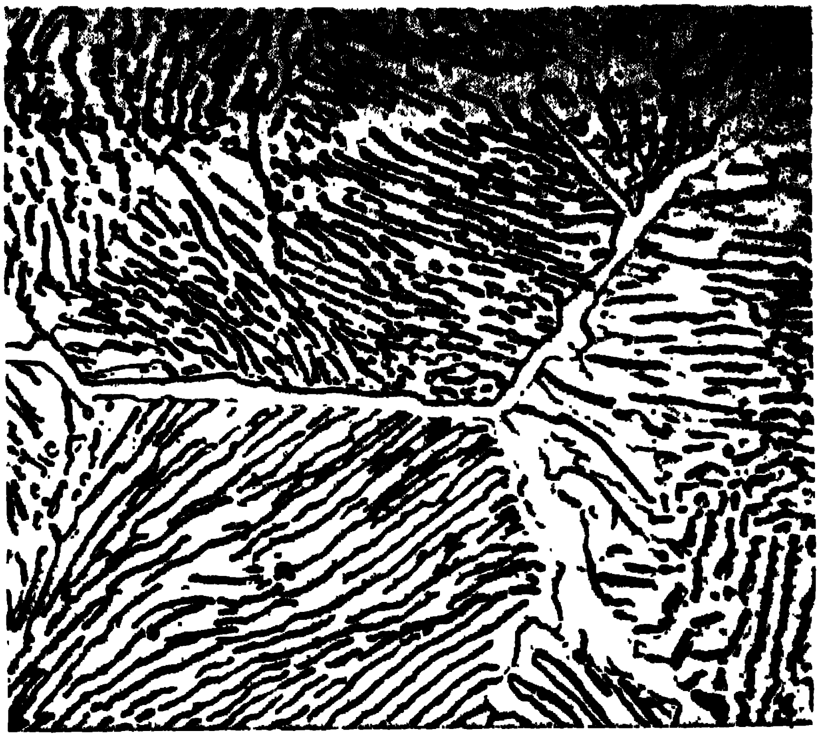


Fig. 7. Typical appearance of lamellar pearlite which contains about 0.8% carbon by weight, the eutectoid composition. 3% nital etch, magnification 750 ×.

190,000 p.s.i., yield strengths of 50,000 to 135,000 p.s.i., and elongations of 16 to 12 per cent. The low hardness of ferrite (70-120 BHN) and the high hardness of cementite (550 BHN) are merged in pearlite to give a net hardness of 197-225 BHN.[228] The higher strengths and hardnesses

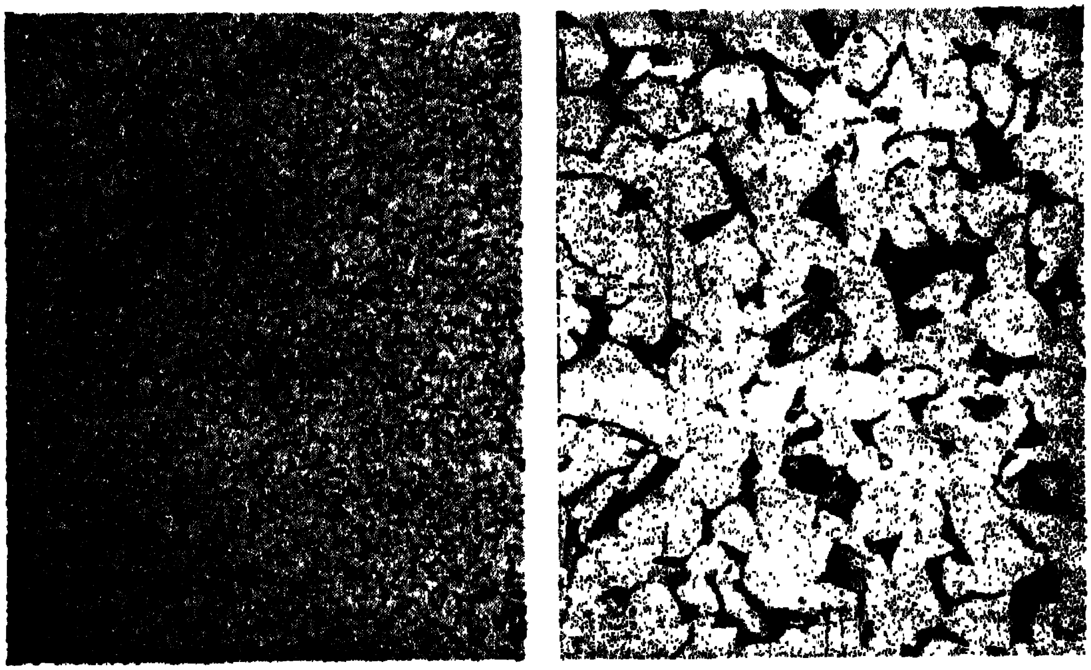


Fig. 8. Representative photomicrographs of low carbon steel. AISI 1020. Note that the microstructure consists of patches of pearlite in a ferritic matrix. 3% nital etch, magnification (left) 150 × and (right) 500 ×.

come from a closer packing of the pearlite lamellae (e.g. of the order of 1,000 Angstroms) which arises from faster cooling rates or lower reaction temperatures. Since pearlite contains 0.8 per cent carbon, the "eutectoid" composition, any iron-carbon alloy having a carbon content less than this concentration will have only a partially pearlitic structure, the remainder being ferrite (cf. Fig. 8). Thus its properties will lie proportionately between those of pure iron and those given above for fully pearlitic iron.

Through appropriate heat treatment, the combined carbon may exist as small globules, instead of as lamellae. Such a structure is called spheroidite. It generally indicates an iron that is more ductile and more easily machined than if the same amount of combined carbon were in the lamellar form. The matrix of the spheroidized tool steel, pictured in Fig. 9, illustrates this type of structure.

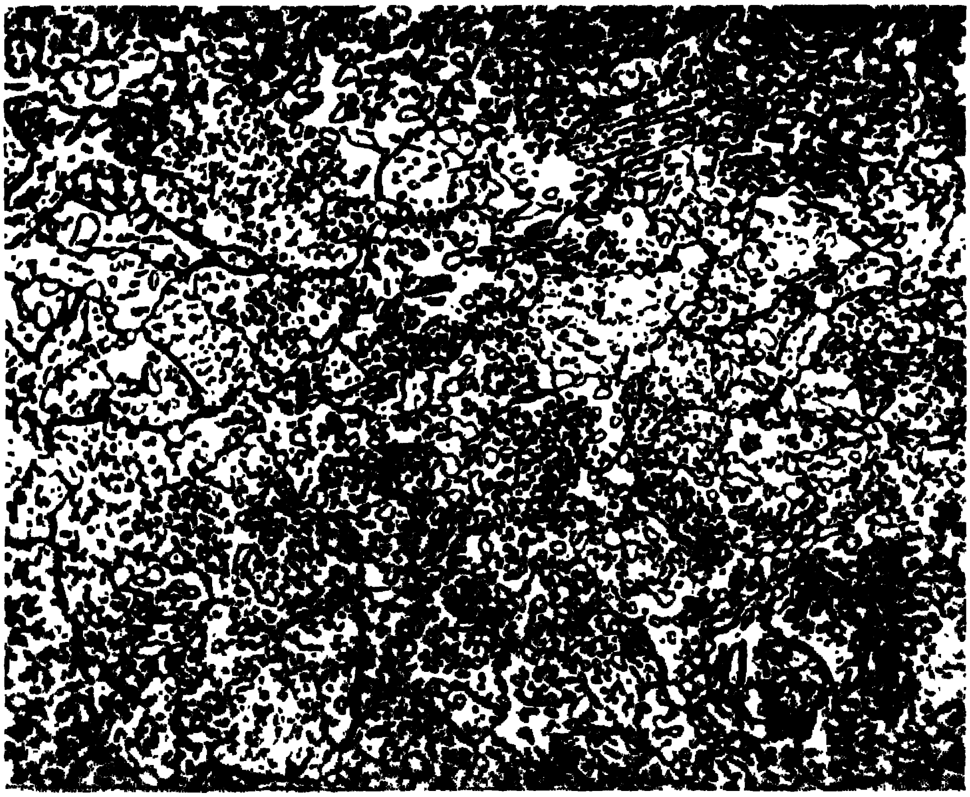


Fig. 9. **Microstructure of 1.10% Carbon tool steel exhibiting spheroidized combined carbon. Note the numerous small globules of carbide. Nital etch, magnifiication 500 X.**

EQUILIBRIUM AND NON-EQUILIBRIUM

It was brought out earlier that high rates of heating and cooling will alter the location of the boundary lines between phases. Therefore, only under extremely slow heating and cooling rates can the temperature-composition limits be considered to represent equilibrium positions.

It is a well established fact that cementite tends to break down into iron (ferrite) and carbon (graphite),

$$Fe_3C \rightleftharpoons 3Fe + C,$$

and this reaction is favored by (a) elevated temperatures, (b) long times at these temperatures, (c) the existence of solid non-metallic impurities of the hexagonal type, (d) higher carbon contents, and (e) the presence of elements that aid decomposition of Fe$_3$C. The graphitization of cementite in low carbon, low-silicon steels may require several years at temperature just under the A$_1$, for example, steels in petroleum distillation systems, in steam pipes, and in weldments.[106,107,108] On the other hand, graphitization occurs much more rapidly in irons containing relatively high carbon, containing elements that strongly promote the reaction when the iron is held between the A$_1$ and the eutectic temperatures, or containing both. Cementite, therefore, is a transitional or metastable phase which tends to fall to the lower-energy (stable) condition of iron and carbon, whenever conditions give it the opportunity.

On the iron-carbon constitution diagram for the metastable system, shown in Fig. 6, are superimposed the phase boundaries of the stable system (dotted lines). It will be noted that at any temperature the iron in equilibrium with cementite is richer in carbon than that in equilibrum with graphite.

EFFECT OF SILICON ON THE IRON-CARBON SYSTEM

To consider iron-carbon alloys merely on the basis of a binary diagram serves only as a simple way in which to approach a more complicated situation. Commercially produced irons and steels always contain other elements in addition to iron and carbon. Some of these are practically unavoidable since they are present in the iron ore, pig iron, or scrap from which iron and steel are produced, or they are picked up in the melting furnace from the fuel, atmosphere, or slag. Other elements are purposely added or maintained at controlled levels in order (a) to combine with, nullify, or remove certain other undesirable constituents already present in the metal and (b) to alloy with the iron or carbon or both so as to alter the properties or response to heat-treatment of the metal, or to direct solidification of the alloy according to either the stable or metastable system.

Added elements may combine with carbon to form carbides, which (a) impart strength, hardness, and abrasion resistance or (b) prevent the forming of certain other undesirable carbides which might impair resistance of the alloy to corrosion. Other elements that go into solid solution in the alloy may improve the strength of the metal, retard corrosion, alter transformation temperatures or rates, and promote secondary hardness. Others may be added to control grain size. Under favorable conditions during the solidification of certain iron alloys, small quantities of magnesium, cerium, some of the rare earths, or other elements may encourage the precipitation of the graphite as compact nodules or spherulites.[102,103,104] (cf. Fig. 10). Without alloying, such irons would have a

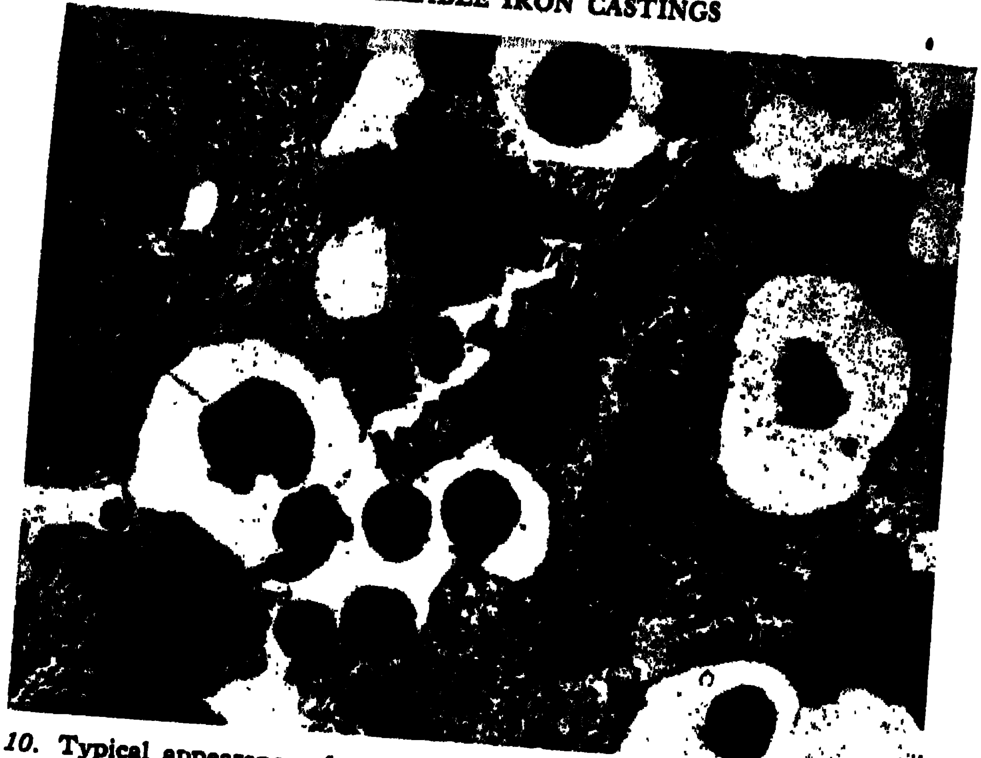


Fig. 10. Typical appearance of nodular cast iron. Note the graphite in nodular or spherulitic form, surrounded by "bull's eyes" of ferrite. The matrix is pearlitic. Nital etch, magnification 500 ×.

typical gray iron structure, consisting of flakes of graphite and pearlite (cf. Fig. 11).

A complete discussion of the effect of alloys is beyond the scope of

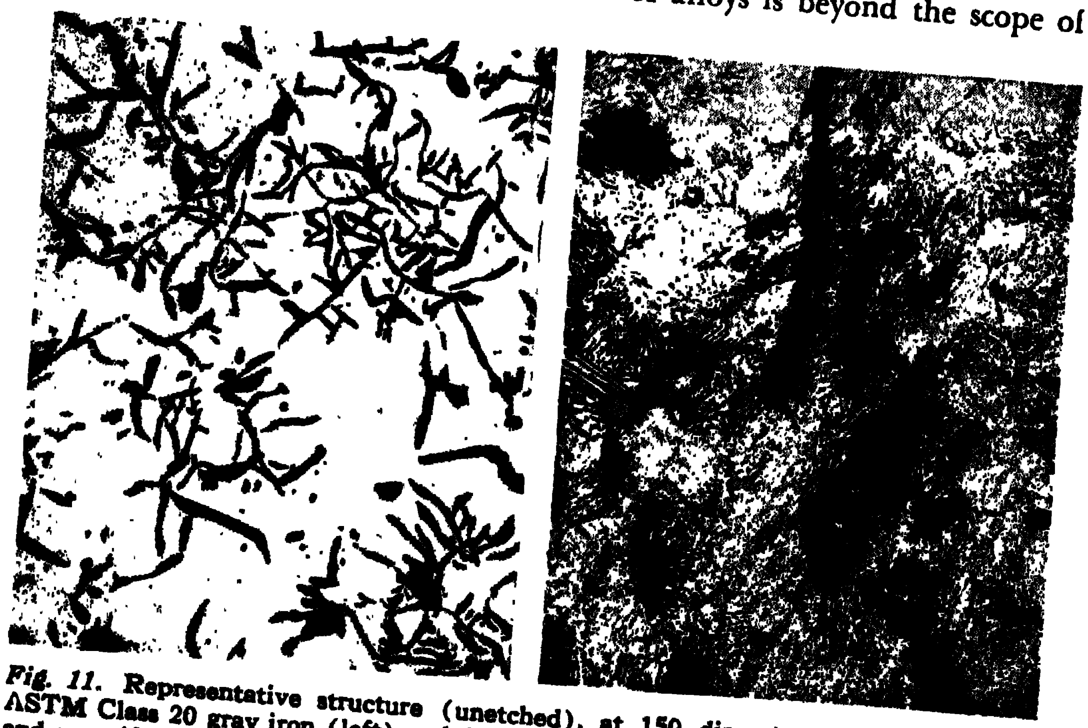


Fig. 11. Representative structure (unetched), at 150 diameters, of an unalloyed ASTM Class 20 gray iron (left) and ASTM Class 50 high-strength gray iron, etched and magnified 500 times (right). The graphite needles as well as the fully pearlitic matrix of the right-hand picture are readily discernible.

this handbook. Further information may be obtained from the several references[17,27,157,158] listed in the bibliography, which cover the subject far more thoroughly. Henceforth the discussion will concern essentially only those elements that may be found in malleable iron.

Malleable iron is a ferrous alloy of such well-balanced composition that under normal freezing rates it will solidify wholly in accordance with the metastable system and yet will be readily converted to the stable system when subjected to suitable heat-treatment. In other words, at room temperatures the as-cast metal has all of its carbon in the combined form (cementite or Fe_3C.) as is illustrated in Fig. 12. As we have seen, this is a hard, brittle constituent, and so, as would be expected, this iron breaks easily, particularly in impact. The fracture of the broken iron is crystalline in appearance (because of shear cleavage through the iron carbide), and hence the material is commonly referred to as "white" iron. Under the microscope the massive carbides are seen to be aligned. This condition is due to the fact that they have a lower freezing point than the austenite, which has previously solidified in a tree-like, or "dendritic" pattern. The carbides therefore must freeze out in the spaces between the austenite dendrites.

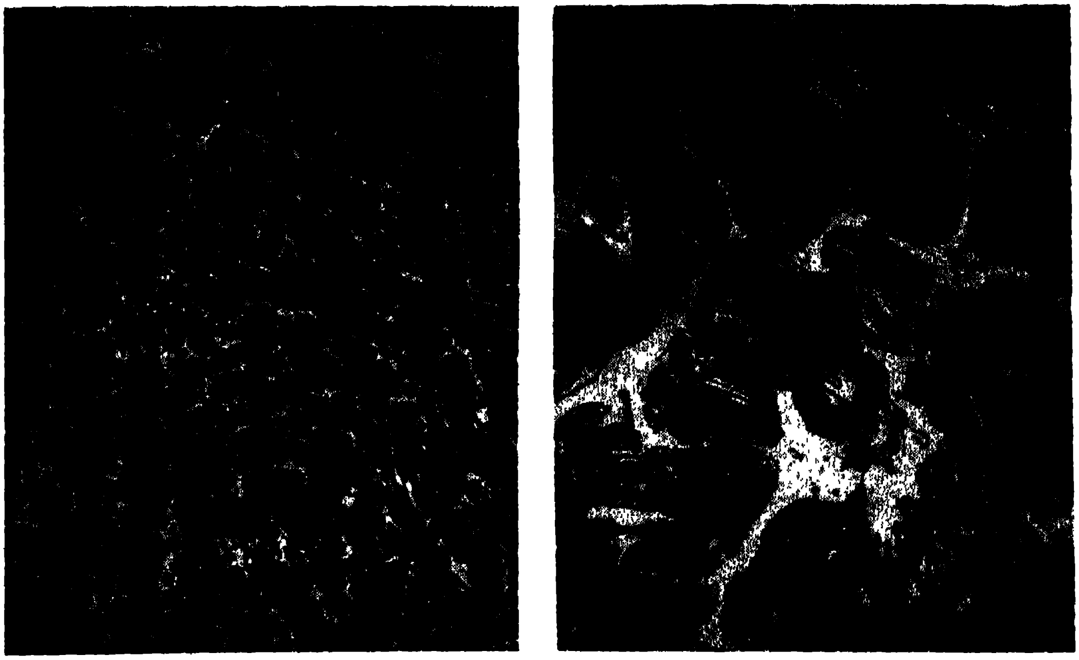


Fig. 12. **Typical appearance of etched white iron at low (100 ×, left) and high (500 ×, right) magnifications. The white areas are spines of carbon in the combined form, called cementite or Fe_3C, a very hard and brittle constituent. The matrix is substantially fine pearlite.**

The white iron castings then pass on to the second essential step in malleable iron production—the "malleablizing" heat-treatment, which causes complete breakdown of the cementite into its constituent elements —iron and carbon. The carbon precipitates in compact aggregates, called temper carbon nodules. These offer relatively little discontinuity to the base substance which is ferrite, or iron, in which are dissolved small quantities of alloys which contribute to the properties (e.g. strength, corrosion resistance) of the material. Thus, with all the hard, brittle cementite removed, we have in malleable iron a strong, tough, readily machinable metal (Fig. 13).

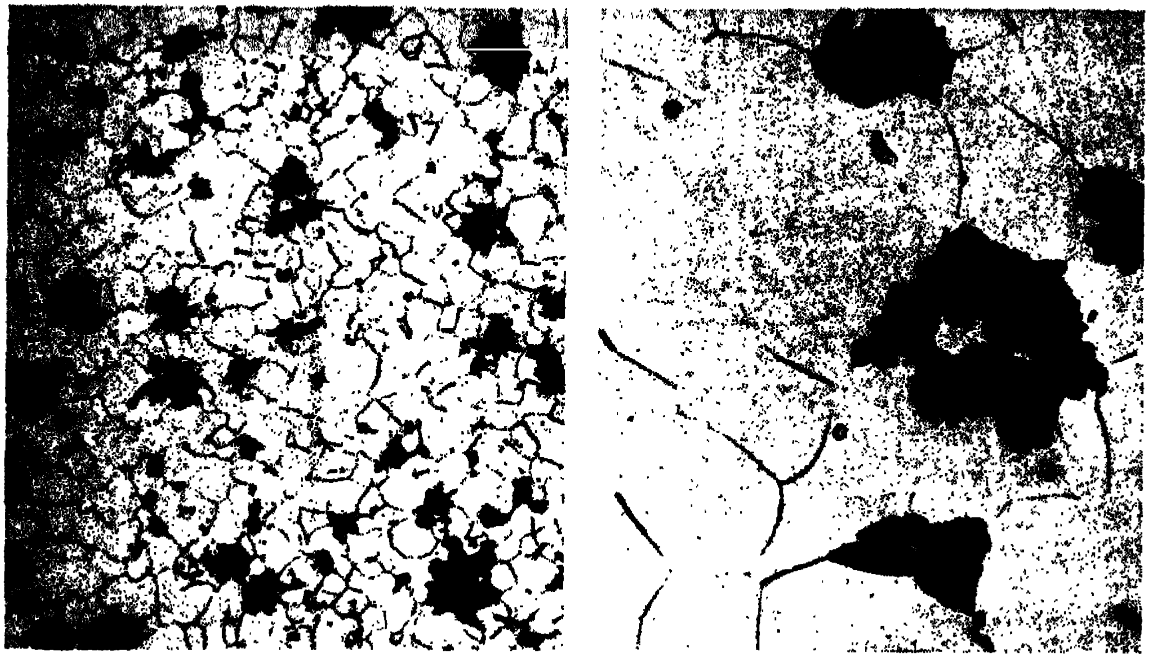


Fig. 13. **Ferritic malleable iron exhibits but two major constituents in the microstructure: ferrite and temper carbon. The dark particles are temper carbon, while the white background material represents the ferritic matrix. Grain boundaries are clearly visible. The small gray particles on the right are manganese sulphide. The etchant was nital, and the magnifications were 100 × (left) and 500 × (right).**

We have said that the chemistry of malleable iron is carefully maintained in balance. This statement refers to the delicate equilibrium between elements that lean strongly toward the stable system by favoring graphite formation, and elements that retard or prevent the breakdown of cementite and thus encourage reactions that progress according to the metastable system. The former are referred to as "graphitizers," the latter as "carbide stabilizers" or "retardants."

Some elements may exert their influence either during solidification or during heat-treatment, or both. Those acting during the heat-treatment may likewise affect the iron either above the eutectoid temperature (i.e. during first-stage graphitization) or during the eutectoid transformation (second-stage graphitization), or during both.

Silicon is one element that is always present in malleable iron. It affects the metal from melt-down time onward, viz., during solidification and malleablization, and carries its effect on into the properties of the final product. The fluidity of molten iron is increased by silicon, which is approximately one-quarter as effective in this respect as is carbon.[159] A change of 1 per cent silicon will vary the length of the Porter-Rosenthal fluidity spiral by about 1 inch (Fig. 14). Though silicon somewhat

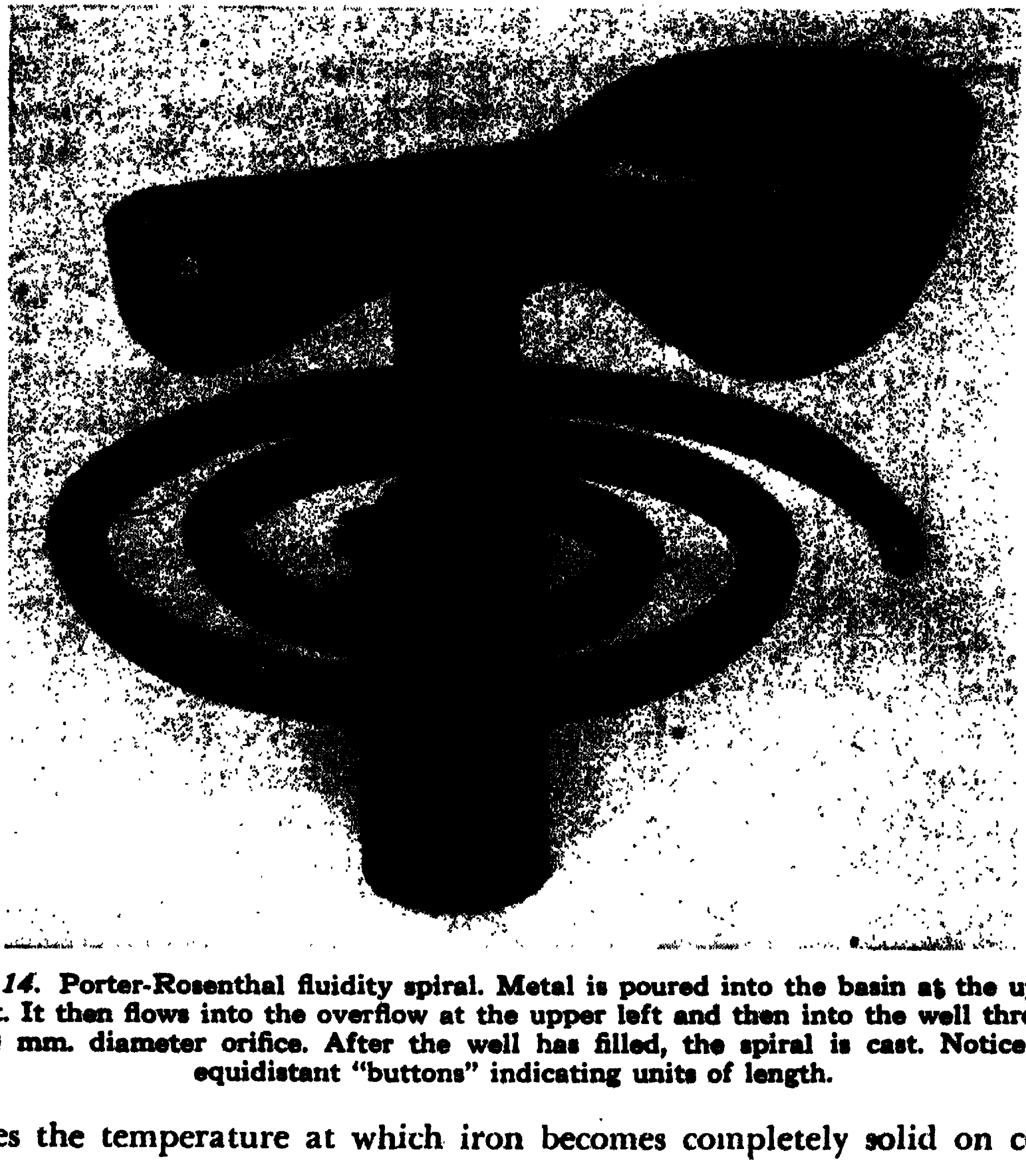


Fig. 14. **Porter-Rosenthal fluidity spiral. Metal is poured into the basin at the upper right. It then flows into the overflow at the upper left and then into the well through a 10 mm. diameter orifice. After the well has filled, the spiral is cast. Notice the equidistant "buttons" indicating units of length.**

raises the temperature at which iron becomes completely solid on cooling, because of a leftward shift of the eutectic composition (0.30-0.33 per cent carbon for each 1 per cent silicon), the net effect is to depress the temperature at which iron begins to solidify. This amounts to a depression of the solidus temperature of about 50 degrees F. per 1 per cent additional silicon at a level of 2.5 per cent carbon. Less shrinkage would be anticipated from this narrowing of the solidification range. In iron-carbon-silicon alloys, eutectic freezing occurs over a temperature range rather than at a single temperature as in the case of the simple iron-carbon alloys.

Aside from its influence on solidification, silicon also significantly alters the location of phase changes in the iron-carbon diagram. With progressively higher silicon contents the austenite field decreases in area, the eutectoid carbon content is lowered, and the eutectoid transformation occurs over a broadening range, the limits of which are raised by greater silicon. A slice through the ternary iron-carbon-silicon diagram at 1 per cent silicon is shown at the left in Fig. 15. Higher silicons that are not counter-balanced by carbide-promoting elements favor solidification according to the stable system. That is, carbon is precipitated as graphite while the iron cools through the freezing eutectic, where austenite, graphite, molten iron, and carbide exist together. Such carbon is known as "primary" graphite. It comes out usually in the form of flakes, which is the common type found in gray cast iron (Fig. 10). Once primary graphite has precipitated in iron, its shape cannot be altered by any method short of remelting. Because of the sprawling form of the graphite, the continuity of the iron matrix is so broken up that, if subjected to sudden impact or stress, the metal fails readily through the weak graphite flakes and via the notches formed at the ends of the flakes in the ferrite.[252] It is for this reason that in the manufacture of malleable iron primary graphitization is avoided at all cost.

Chemical analysis has shown that silicon is located mostly in the ferrite.[199,273] The strong tendency of silicon to promote primary graphitization, when other conditions are favorable, has already been noted. It is therefore obvious that excessive silicon contents must be avoided in malleable iron production, particularly when the carbon level is high, or the cooling rate is low, or both. However, if the silicon content is too low, though the iron may freeze entirely as white iron, the dissociation of cementite during the subsequent heat-treatment will be very sluggish and will require prolonged times to effect a complete breakdown of the massive carbides. At 1.4 per cent silicon, an iron will malleableize in half the time of one with only 1.0 per cent silicon. Thus it is of the utmost importance that silicon be closely controlled, being governed by such factors as carbon level, melting conditions, degree of superheat, relative amounts of other graphitizers present, carbide stabilizing pressure in the iron, and the cooling rate (which is largely a function of section shape and thickness and of whether or not chills are used). In solid solution, silicon increases the tensile strength (roughly 10,000 p.s.i. per 1 per cent silicon)[157,79,250] and hardness (some 20 to 25 BHN per 1 per cent silicon) but reduces ductility and shock resistance. The nil-ductility-transition temperature is raised and the susceptibility to temper (or "galvanizing") embrittlement is increased with higher silicon contents.[218]

The carbon nodule count and graphitizing potential are apparently related to the rate of oxidation during melting as measured by per cent silicon loss.[195] The graphitizing rate of iron that has been melted under highly oxidizing conditions will be relatively low, even after the silicon has been restored to normal levels by ferrosilicon additions before tapping. If the silicon content in such an oxidized melt is stepped up to above the typical range, the graphitizing rate and nodule count will return to normal. The aluminum and calcium contents of ferrosilicon have been found to be instrumental in inoculating irons.[212]

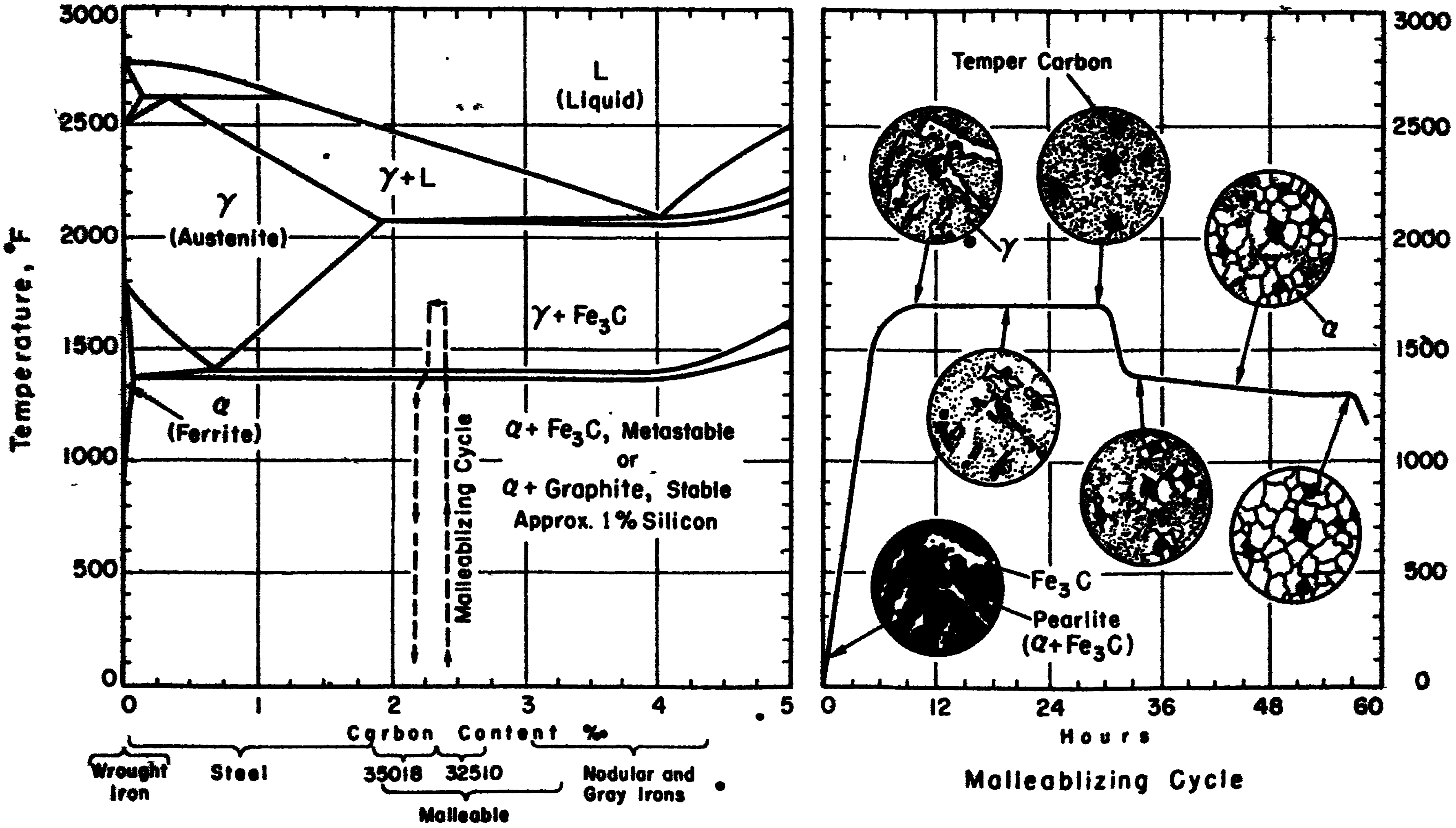


Fig. 15. Constitutional and heat-treating diagrams for malleable iron. The malleabilizing cycle is superimposed on the constitutional diagram on the left, while the change in microstructure as a function of the malleablizing cycle is depicted in the right hand sketch.

EFFECT OF COOLING RATE ON FREEZING

The direction in which an iron-silicon-carbon alloy solidifies is highly sensitive to the rate at which the metal cools through the eutectic freezing range. Slow cooling permits the alloy to be in the range for a longer time than would rapid cooling. The longer period encourages graphitic nucleation and growth of flakes. On the other hand, rapid cooling does not give sufficient time for the iron to be in the eutectic range and for graphite to form. Therefore, a relatively fast-cooled iron-carbon-silicon alloy will be free from primary graphite. At about 2000 degrees F., shortly after the iron has completely frozen, half or more of the carbon is dissolved in the solid solution of austenite, while the remainder combines with iron to form pools of cementite (the "massive" carbides) between the austenite dendrites, which originated and grew during cooling from the liquidus to the eutectic. Heavy castings with thick sections cool much more slowly than do thin-sectioned ones. Therefore, primary graphite would be more apt to occur in such heavy work were certain precautions not taken to prevent its formation (e.g. melt-chemistry control, superheating, chilling, alloying, et al).

THE FREEZING OF WHITE IRONS

It has been explained that if both composition and cooling rate during solidification are properly adjusted in relation to one another, the iron-carbon-silicon alloy will freeze as white iron, that is, with all its contained carbon combined as cementite, Fe_3C. A composition of 2.5 per cent carbon and 1 per cent silicon cast in, say, a section a half-inch thick in a green sand mold would satisfy these conditions. What happens during cooling from the molten state down to room temperature may be determined from Fig. 15. Solidification is initiated at the mold-metal interface, where the first crystals of primary austenite start to freeze. As the temperature of the metal drops because of heat transfer to and through the sand mold, these austenite crystals grow.

Whenever a molten metal cools, it contracts, as is evidenced by depression of the mercury column in an ordinary thermometer during cooling. In the eutectic range further contraction occurs. Still more shrinkage ("solid contraction") results from cooling solidified metal, although to a different degree from that which occurs in the liquid state. If surface depressions or voids are to be prevented in castings, the total metal contraction must be compensated by a supply of additional molten metal from reservoirs, or "risers," that are attached to the heavier sections of the castings and are the last to freeze. In metals of malleable iron composition the freezing range is relatively wide and, unless the thermal gradients in the casting are very steep, this compensating supply of liquid iron must flow through the narrow and tortuous channels left between the growing dendrites to those parts where freezing is most advanced, particularly after solidification is 60 per cent or more completed.[118] The practical aspects of feeding or risering are briefly covered in the chapter on Design.

As the temperature is lowered, growth of the austenite dendrites continues until further crystallization is obstructed by contact of crystals growing in opposite directions from different centers, or until the temperature has been reduced to where the eutectic ("ledeburite") forms in the spaces between the austenite dendrites. During eutectic freezing, "secondary" crystals of austenite (indistinguishable from the primary) and "massive" carbides precipitate out over a narrow temperature range until the metal has been completely solidified. On continued cooling at a fairly rapid rate, practically no change occurs until the austenite transforms at the eutectoid range into alternate plates of ferrite and cementite —pearlite. Hence, at room temperature the structure of white iron of malleable iron composition consists of massive carbides and pearlite.

EFFECT OF OTHER ELEMENTS ON THE IRON-CARBON-SILICON SYSTEM

Elements dissolved in molten iron-carbon alloys may freeze more in association with either the ferrite or carbide phase, or they may react to form inclusions. The distribution of a certain element among the several phases depends upon the concentration of other elements present.

Sulfur, which is always present in commercial melts, will react preferentially with manganese to form manganese sulfides or complexes of iron, manganese, sulfur, and oxygen, which separate out as a discreet phase when the iron is freezing. Although the specific gravity of manganese sulfide is lower than that of the melt, most of the sulfide is trapped during solidification before it can rise into the slag and thereby be removed. These small dispersed inclusions do not impair the properties of the metal and, except when nucleating temper carbon, they play no part in the graphitizing process.

Theoretically, 1.7 parts of sulfur are needed to combine with one part manganese to form MnS. However, in view of the relatively small quantities of these two elements and mass law considerations, it is normal commercial practice to maintain the manganese slightly in excess of the theoretical requirements. A manganese content of three times the sulfur or two times the sulfur plus 0.15 per cent is common. Since both manganese and sulfur are carbide stabilizers, if either is allowed to rise much above that needed to form the sulfide, it will exert a stabilizing effect on the iron carbides.[202,209] Excess manganese has little influence on the solidification process and only weakly retards first-stage graphitization (Fig. 16). On eutectoid graphitization, however, manganese is strongly carbide-stabilizing (Fig. 17). Therefore, in making standard malleable iron, it must be kept in close control, particularly with short annealing cycles, in order to insure fully ferritized iron. In making some alloyed

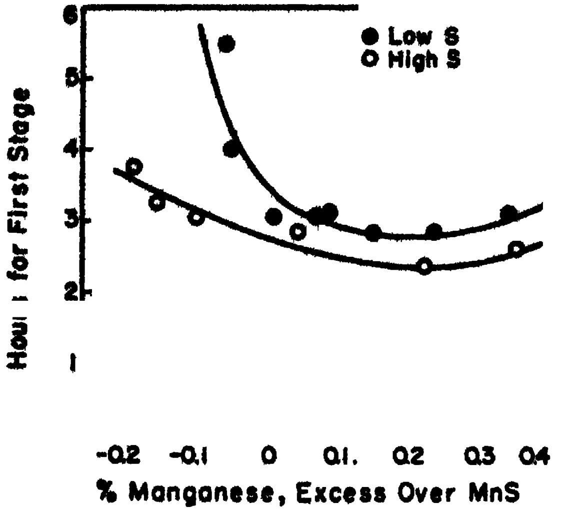


Fig. 16. **Effect of manganese content on first stage graphitization.**

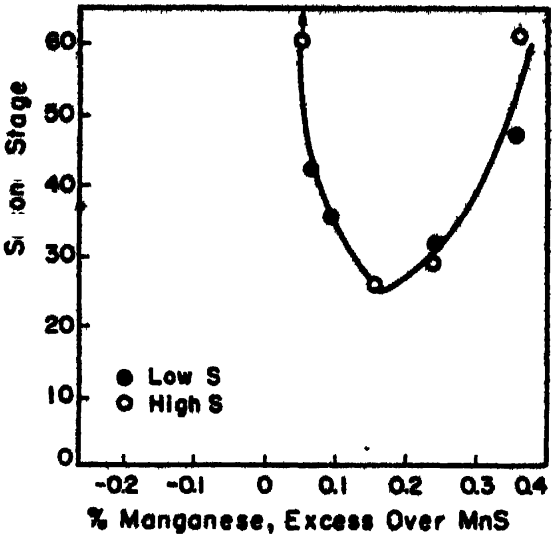


Fig. 17. **Effect of manganese content on second stage graphitization.**

pearlitic malleables, as will be discussed later in this chapter, the use of excess manganese as a second-stage graphitization retardant is employed to advantage. Linear relationships exist between the manganese (over that required to form MnS) and both Curie temperature and manganese

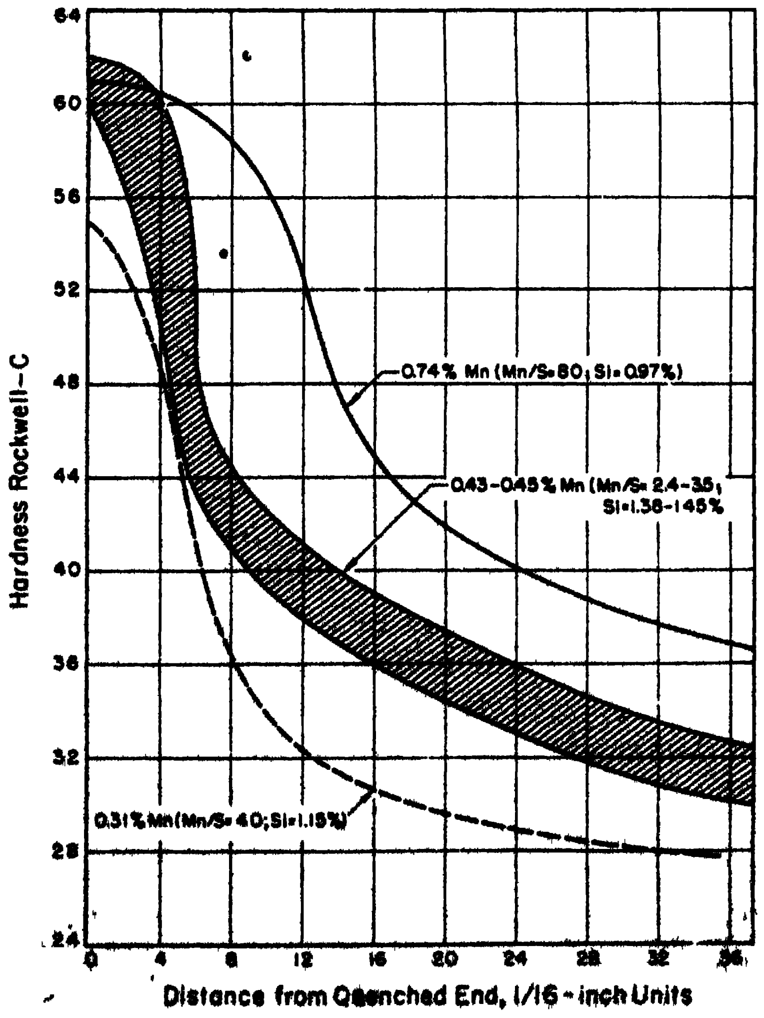


Fig. 18. **Effect of manganese on hardenability of malleable iron. Standard Jominy hardenability test specimens, quenched in water in the standard fixture, were austenitized at 1600° F. Rockwell "C" hardness numbers were determined at various distances from the quenched end.**

contained in the cementite.[255,278] Higher manganese contents increase hardenability[92]; cf. Fig. 18. Austenitic malleable irons may be produced with very high manganese contents (viz. 8 to 13 per cent) along with 3 to 5 per cent nickel or copper.[257]

When there is sufficient excess sulfur present (e.g. Mn/S less than 1.0), primary graphitization is suppressed, thus permitting heavier sections (e.g. 4-inch and over) to be cast mottle-free.[202,205] Each 0.01 per cent surplus sulfur is sufficient to neutralize the graphitizing influence of 15 times that amount of silicon.[163] Excess sulfur retards both first and second stages of the malleablizing anneal.[203] Even prolonged holding high-sulfur irons in the vicinity of the A_1 temperature seldom results in complete malleableization. When there is not enough manganese present to combine with all the sulfur, the unreacted sulfur chemically joins with iron to form iron sulfides. Graphite nodules forming on these FeS nuclei tend to be very compact and ordinarily are spherulitic in shape (Fig. 19), such as are found in some white-heart malleable irons[158] and in sulfur-alloyed pearlitic malleable irons.[205] Higher sulfur melts tend to have reduced fluidity, presumably because of the sulfide particles present.[210]

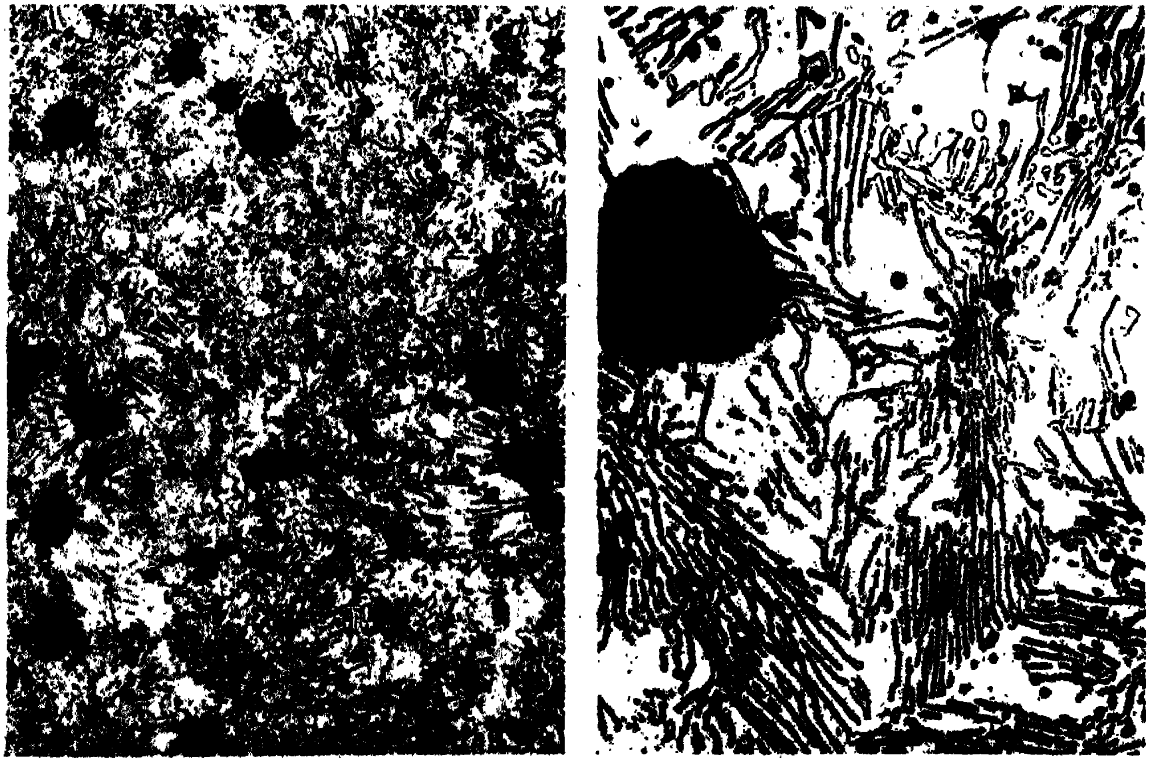


Fig. 19. **Representative microstructure of malleable iron with insufficient manganese to balance the sulphur content. Ratio of manganese to sulfur was approximately 1.00. This sample was given a standard anneal. Note the spherulitic temper carbon and the retained coarse pearlite. Nital etch, magnification 100 × (left) and 500 × (right).**

Chromium is present in all irons in at least trace amounts, being carried over as a residual from scrap in the melting furnace charge. It is found to be divided between carbide and austenite in the ratio of 5 to 1.[164] Since chromium is a strong carbide stabilizer, amounts in excess of about

0.04 to 0.05 per cent are very undesirable in malleable iron. In an iron containing 1 per cent silicon, for each 0.01 per cent chromium an increase of approximately ten per cent is required in the time needed to complete graphitization of the massive carbides.[166] A still much longer time is necessary in order to break down secondary carbides in the eutectoid transformation range. If it is known that a melt of malleable iron does contain a relatively high chromium content, its strong stabilizing tendency may be offset by the addition of an effective graphitizer, such as a small quantity (e.g. 0.0015 per cent) of boron in the form of ferroboron. Increasing the silicon in the melt by eight times the amount of excess chromium can serve to counterbalance the chromium,[166] although silicon should be added cautiously so as not to promote the formation of primary graphite.

Phosphorus is another element that is always present in malleable iron (0.05-0.18 per cent), coming originally from the iron ore. It is about half as effective as an equal amount of carbon in aiding fluidity.[159] Physically it forms a phosphide eutectic with a relatively low melting point. This extends the range of eutectic freezing, thus favoring primary graphitization. If the phosphorus, carbon, and silicon of a certain iron is known, its liquidus temperature ("L") in degrees F. may be approximated[159] from the formula:

$$L = 2981 - \left(\%C + \frac{\%P}{2} + \frac{\%Si.}{4}\right) 218$$

The upper eutectoid temperature is increased linearly with higher phosphorus contents, but the lower critical is unaffected.[79]

Despite the fact that phosphorus contributes appreciably to strength (some 5,000 p.s.i. for each 0.10 per cent phosphorus[157,167,79]), it is desirable to keep phosphorus under 0.15 per cent, for it raises the transition temperature in impact[211]; cf. Fig. 20. High phosphorus and silicon contents, together with rapid cooling of the iron from within the "blue heat" range of 1100 to 450 degrees F., will raise the nil-ductility-transition temperature sufficiently for the metal to become brittle at or above room temperatures.[168] The length of time a susceptible iron is held at the embrittling temperature is not important.[259] The worst embrittlement results when susceptible irons are quenched from about 850 degrees F. This is approximately the same temperature as a hot dip galvanizing bath; galvanizing such castings may render them brittle. Hence the phenomenon is commonly referred to as "galvanizing embrittlement." The broken fractures of castings that exhibit temper brittleness have a crystalline rather than the customary dark and velvety appearance. While micro-examinations reveal nothing other than the typical ferrite and temper carbon structure of standard malleable iron, on observing a fractured surface one can see that the failure is intergranular, instead of transgranular.[169] Embrittlement cannot be revealed by conventional

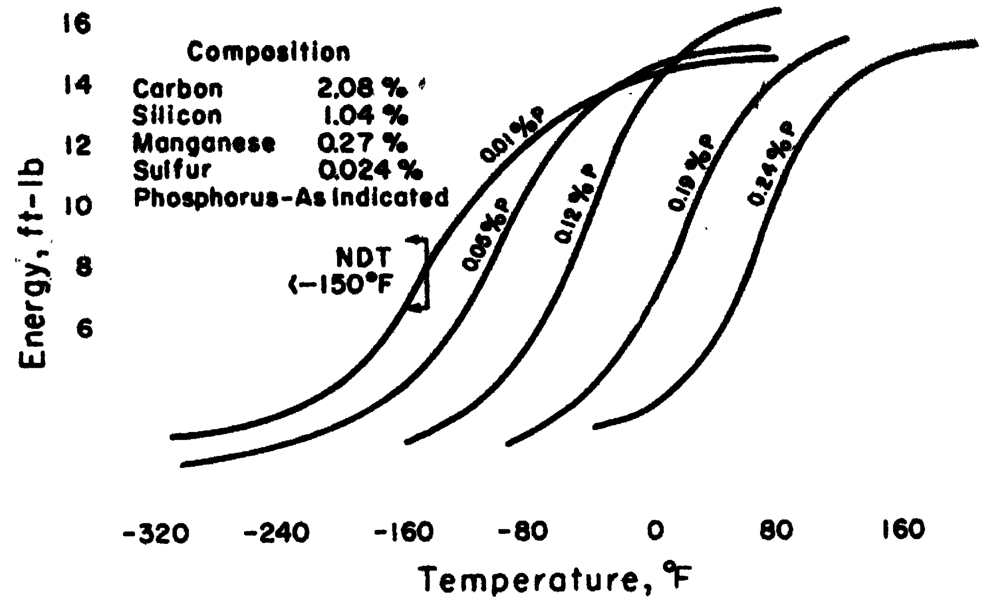


Fig. 20. Charpy V-notch transformation curve for malleable iron as a function of phosphorus content. Note that the nil-ductility-transition (NDT) temperature is lowered as the phosphorus content decreases.

static tests, such as hardness[214] or tensile,[108] but it can be disclosed by various impact tests (Izod, Charpy, Humfrey, drop-weight, and explosion). Particularly in the presence of a stress raiser, high speed loading will disclose an embrittled condition more readily than will slower rates of load application.[258] Some small differences between ductile and brittle states are reported to be disclosed by prescribed corrosion technique, by electron diffraction studies, and by elastic modulus determinations by the electrostatic oscillation method.[259]

Several means are applicable for avoiding or reducing the danger of galvanizing embrittlement:

(a) Keep the combination of silicon and phosphorus contents below the critical levels established by Bean[169] and Sandelin.[214]

(b) Cool the casting rapidly to room temperature from no lower than 1150 degrees F. upon completion of second-stage malleablization.[168,171,215,216,258] Since it is standard practice in many plants today to air quench from just below the A_{r_1} after the annealing cycle is finished, the possibility of temper embrittlement is automatically eliminated, even if the castings are subsequently galvanized.

(c) Alloy the iron, e.g. with copper[170,214] or with molybdenum.[216,217]

(d) Cool slowly from the embrittling temperature, e.g. 850 degrees F.[168,214] This, however, is impractical for galvanized work because slow cooling is detrimental to the hot-dip coating.

(e) Hold the iron at some temperature under the embrittling temperature range.[259] The recovery of ductility by this method is much slower than by method "b" above, viz. reheating to 1150-1250 degrees F. and rapidly cooling. The more the iron composition favors brittleness, the longer the material will have to be held at the low ductility-recovery temperature.

In addition to carbon, silicon, manganese, sulfur, chromium, and phosphorus certain other elements are usually found in trace quantities in standard malleable irons. These generally arise from the melting stock, scrap and pig iron. Small amounts of copper and nickel (up to about 0.1 per cent) and 0.02-0.05 per cent molybdenum are commonly present but at these low levels have little or no effect on the response of the iron to heat-treatment or on its mechanical properties.

Copper is soluble in iron at room temperature up to about 0.5 per cent and in larger amounts in the presence of high silicon or nickel or both. Since copper in solid solution contributes some resistance to corrosion,[178] small additions are sometimes made where applications of the material are to be in moderately corrosive environments. One per cent copper content has been found to aid the resistance of malleable iron to attack by atmospheres of sulfurous gases,[100] such as may be encountered near heavy industry or in railroad roundhouses. Copper has a primary graphitizing influence on solidifying malleable irons that is equivalent to one-tenth that of silicon. Therefore, to avoid increased mottling tendencies, the silicon content should be reduced by 0.1 per cent for each 1.0 per cent copper added. White irons containing up to about 1.2 per cent copper malleableize faster than unalloyed compositions, particularly when the heating rate up to the first-stage holding temperature is relatively slow[174] or when the iron has been given a pretreatment of at least two hours at about 600 degrees F. before being raised to the first-stage malleablizing temperature.[98] Copper is roughly half as influential on secondary graphitization as is silicon.

Copper additions to malleable iron improve the mechanical properties by strengthening and hardening (Fig. 21) the ferrite,[292] by refining the temper carbon, and by permitting precipitation hardening. The effect of such addition is greater when made to an iron with carbon in the upper part of the malleable range, than when made to an iron with a carbon in the lower part of the range. In the case of the lower carbon irons the strength values are already somewhat higher. Molten white iron can dissolve somewhat more than five per cent copper, but the solid solubility of copper in austenite is only 3 to 3.5 per cent and, as noted above, its solubility in ferrite is only about 0.5 per cent at room temperatures.[96] When present in malleable iron in excess of its solid solubility in ferrite, copper precipitates through the cooling matrix in the form of fine globules that are resolvable only at very high magnifications. Copper additions of up to 2 per cent lower both the bottom of the eutectoid range and the M_s temperature by from 12 to 20 degrees F. for each 1 per cent additional copper.[174] Copper may also be used in conjunction with about one-third to one-half as much molybdenum to produce high-strength

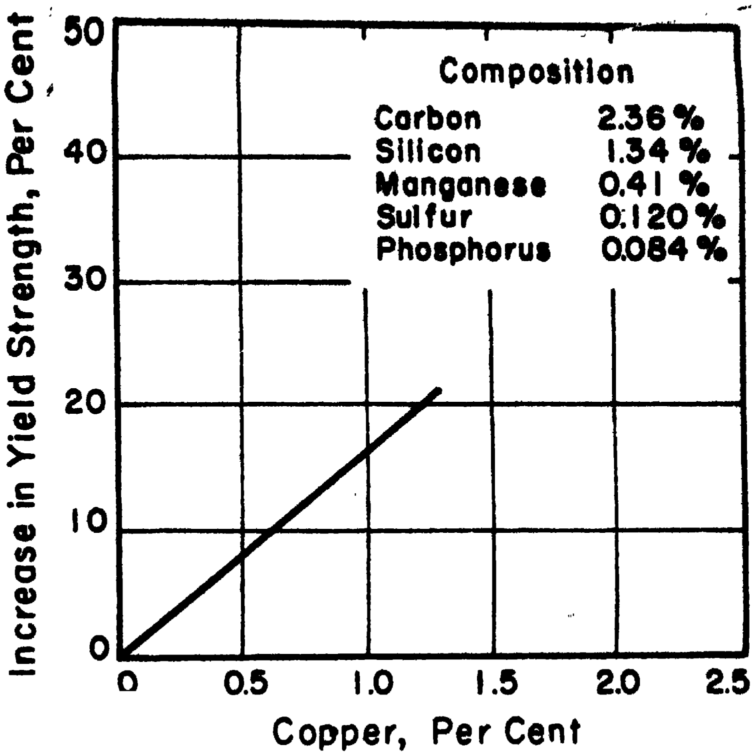


Fig. 21. **Influence of copper on the yield strength of malleable iron.**

ferritic malleable irons (cf. Chapter VII, "Alloyed Malleable Irons"). It also increases the hardenability of iron in direct proportion of the percentage present.[276] Copper bearing malleable castings are less prone to develop temper embrittlement than are unalloyed malleables.[170,214]

Molybdenum moderately retards both first- and second-stage graphitization.[177] The addition of 0.5 per cent molybdenum improves tensile strengths by several thousand p.s.i. and increases hardness without any sacrifice in elongation.[101] This element also helps to stabilize the structure and to maintain the high properties of pearlitic malleable irons when exposed to temperatures up to about 1200 degrees F.[81] As noted above under copper, when molybdenum and copper are added in proper proportions to malleable iron, the carbide-stabilizing influence of the molybdenum is counterbalanced by the graphitizing effect of the copper. The resulting (ferritic) alloyed malleable iron has strength and corrosion-resisting properties that are superior to those of standard malleable iron. Molybdenum lowers the impact transition temperature[217,218]; so it could therefore be utilized in preventing temper embrittlement in susceptible irons.

Although some traces of nickel are usually present in malleable irons, it is not commonly employed as an alloying element. It has a graphitizing influence similar to that of an equal amount of copper[175] and its effect on the mechanical properties of malleable iron is of the same order as copper.[254] Although nickel contributes some solution strengthening, it does so at the expense of ductility. High nickel contents (e.g. 15 per cent) have been employed to develop a chill-cast austenitic malleable iron for special service requirements.[229] This particular metal combines the useful qualities of high machinability, exceptional corrosion resistance, and good mechanical properties (70,000 p.s.i. tensile strength, 50,000 p.s.i. yield strength, 5 per cent elongation).

Besides the residuals already mentioned, there may be a number of other elements present in trace amounts in regular white iron melts. A few hundredths per cent of titanium may appear from (a) certain pig irons, (b) alloy steel scrap, and (c) melting furnace refractories. Titanium is a strong graphitizer and even small quantities impair physical test results. While vanadium in the melting stock is largely lost through oxidation, even residual amounts remaining in the iron will retard graphitization. Its effect is additive to that of any chromium in the iron. The presence of tin is extremely objectionable, because it combined with the sulfur of manganese to form an allotriomorphic sulfide,[175] which potently retards graphitization.

Boron, in amounts up to 0.1 per cent, exerts a graphitizing effect and therefore hastens malleablization (although at some sacrifice to physical properties). In view of this phenomenon, 0.001-0.002 per cent of boron may be purposely added as ferroboron to melts known to contain a relatively high level of carbide stabilizers (e.g. chromium), in order to permit full graphitization without extending the normal malleablizing cycle. Boron is unique in that when it exceeds 0.1 per cent it reverses the above effect and becomes a strong carbide stabilizer. Hence, when boron is added in small amounts to several or more successive heats, routine analyses are recommended to prevent it from building up in excess of a few hundredths per cent through the sprue and metal returns in the furnace charge. As the quantity of boron in the iron is raised, the carbon nodule count increases, the nodules become smaller in size, and a preferred dendritic orientation develops (cf. Fig. 22).[261]

Like titanium, aluminum is a powerful deoxidizer and graphitizer. Small percentages act initially as deoxidizers, which aid both primary and secondary graphitization. When enough aluminum has been added to effect complete deoxidization of a particular melt and to leave some aluminum in excess, complex carbides will form.[176] Increasing aluminum contents of the order of a few hundredths per cent in a melt will initially reduce the carbon nodule content. Then a reversal takes place and the nodule count rises rapidly.[227] A few foundries find it expedient to add minute and closely controlled quantities in order to counteract tramp elements present in certain local pig irons that they are obliged to use. In general, however, aluminum tends to impair mechanical properties, and its use in the malleable foundry is avoided.

Occasionally strong carbide stabilizers may be added to iron in amounts of the order of several hundredths of one per cent for the purpose of permitting white iron to be cast in abnormally heavy sections

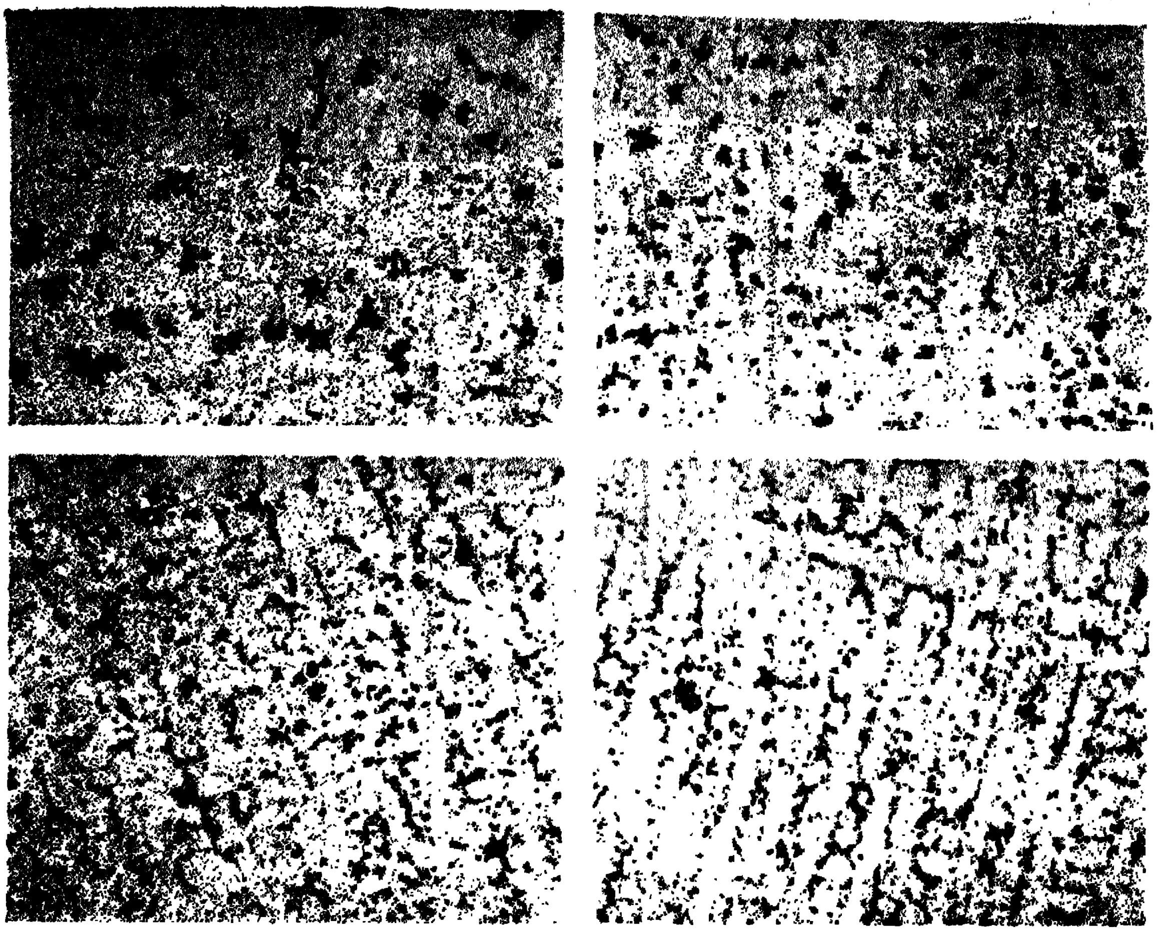


Fig. 22. **Photomicrographs illustrating effects of increasing boron additions on nodule size and distribution in malleable iron. As increasing amounts of boron are added, nodule count increases and the shape compacts. Also note that increasing boron content develops a decided tendency toward preferred dendritic orientation. Nital etch, magnification 100 X.**

A 0.001% B	B 0.004% B
C 0.006% B	D 0.010% B

without mottling. Bismuth[226] and tellurium[225] would be included among such retardants. Small amounts of certain graphitizers (e.g. boron, silicon) may be added along with the primary graphite preventive, so as to counteract the retarding influence of the latter during malleablization.[223,224] Fig. 23[219] illustrates how tellurium can be added for the purpose of carrying higher silicon contents, which favor short-cycle heat treatments. Additions of 0.025 per cent bismuth and 0.003 per cent boron have made possible the casting of white iron in sections up to 5 inches which malleableize fully when put through a regular annealing cycle.[219] Subsequent research[277] has indicated that in 4-inch sections bismuth additions of up to 0.10 per cent have no greater beneficial effect than 0.01 per cent. Additions of bismuth made to iron at 2750 degrees F. suppress mottling more than when made at 2600 degrees F. It is suspected that, in order to exert its maximum influence, the additive must volatilize in the iron; i.e. the temperature of the iron must be higher than the

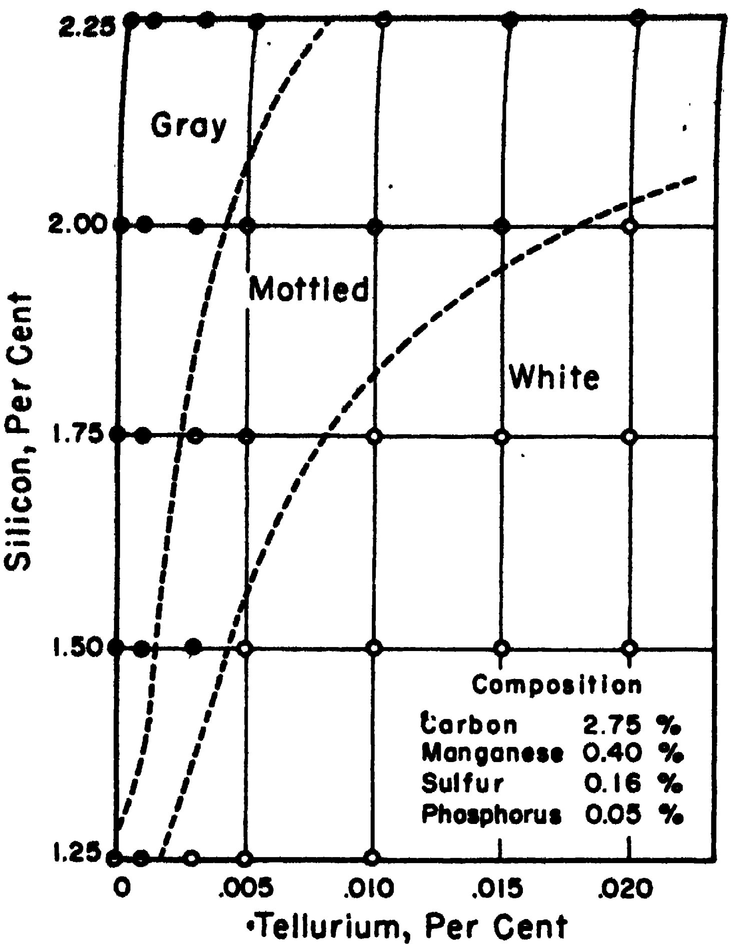


Fig. 23. **Effect of tellur
um and silicon content c
primary graphitization (
white iron.**

boiling point of the additive. (Bismuth boils at 2640 degrees F.) Fig. 2
shows the relationship of white irons at various carbon and silicon leve

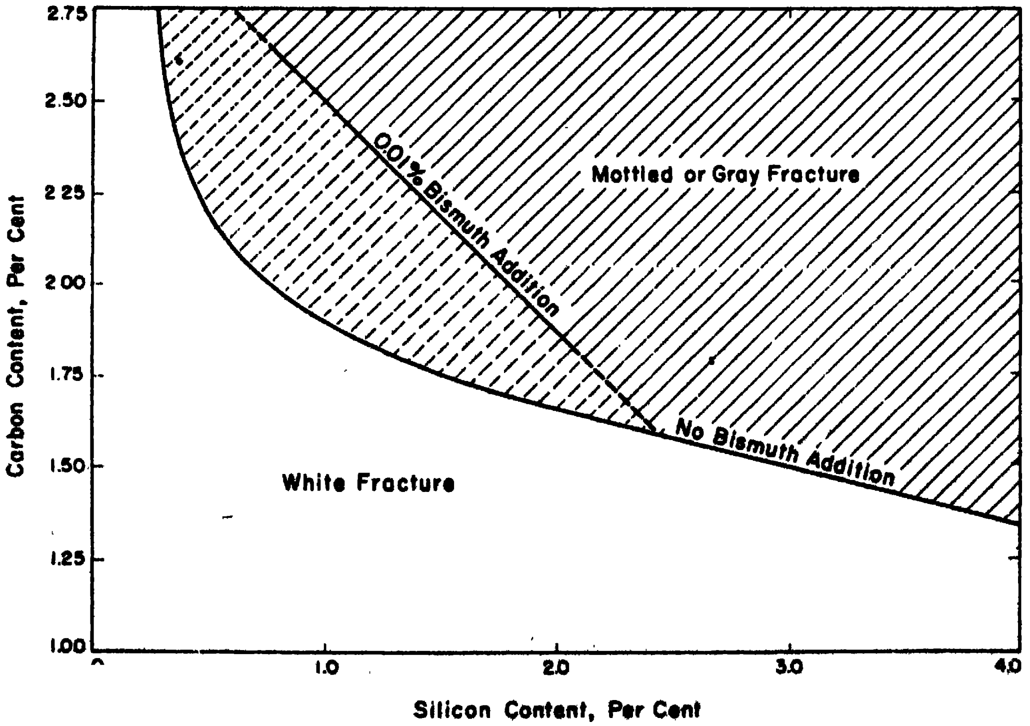


Fig. 24. **Effect of carbon, silicon, and bismuth on the mottling tendency of 4-inch by 4-inch sections of malleable iron.**

with and without 0.01 per cent bismuth additions. It is apparent that bismuth exerts its greatest influence at about 1.0 per cent silicon, tapering off at higher silicon levels up to approximately 2.5 per cent silicon, above which it is effective. A number of other alloys have been tried successfully for the prevention of primary graphitization.

The way in which elements affect graphitization is generally related to how they are proportioned between the cementite and ferrite-austenite phases of the iron. Those that are found mostly in the carbide phase are usually retardants, while those more highly partitioned in the ferrite (or austenite) promote graphitization. The phase in which some of the common elements are mostly found in malleable irons may be determined from Table 3.[273]

TABLE 3. THE PARTITIONING OF ELEMENTS IN MALLEABLE IRONS

Cementite	*Ferrite-Austenite*
Vanadium	Silicon
Chromium	Copper
Molybdenum	Nickel
Manganese*	Cobalt
Phosphorus	Aluminum
Sulfur**	

* When Mn/S > 3. ** At low Mn/S (e.g. Mn/S < 2.).

One avenue of research on malleable iron has been directed toward alloys that would possess high strengths and high elastic moduli in medium and heavy sections after a very short heat treatment. Some of the alloys which have been developed[274,275] require carbon contents (1.25-1.85 per cent) well below the normal composition range for conventional malleable irons. Steel melting techniques must be at least partially followed. Through control of the other elements in the melt and appropriate slagging practice, plus proper alloying (e.g. copper, silicon, chromium, bismuth, boron, tellurium) and a short-cycle heat treatment, the resulting structure consists of fine compact temper carbon nodules throughout a pearlitic matrix. The relatively low total carbon contributes to a higher modulus of elasticity, and the pearlitic matrix promotes excellent tensile strength. While such special irons may satisfy certain particular applications, to date their production has not been of any great consequence.

Tables 4 and 5 summarize the effects of a number of chemical elements and processing variables on malleable iron graphitization[175,200,220,221,222,256,268,260,270,271,272] The range of tramp elements that may be found in pig irons is given in Table 6.[221]

In concluding this discussion on the effect of elements on malleable irons, the influence of dissolved gases originating from the melting furnace atmosphere should be mentioned, for they affect the fluidity of white iron, the hot-tearing tendency, the mechanical properties, the cast-

TABLE 4. EFFECT OF ELEMENTS ON THE GRAPHITIZATION OF MALLEABLE IRONS

Element	*Primary Graphitization (Mottling)*	*Secondary Graphitization*		*Nodule Count.*
		First Stage	*Second Stage*	
Aluminum	– St. Pro. if over 0.1%	– Pro. up to .2-.3% St. Ret. over .6%	– Pro. up to 0.05%	St. I. (>0.05-0.1%)
Antimony	– U	– N	– Pro. under 0.006% – Ret. over 0.01%	N.
Arsenic	– N	– N. up to 0.4%	– N. up to 0.4%	
Beryllium	– St. Pro.	– Pro.	– Pro.	
Bismuth	– St. Ret. (0.01%)	– W. Ret.	– W. Ret.	W. I.
Boron	– Pro. in small amounts	– St. Pro. up to 0.03% – St. Ret. above 0.03%	– St. Pro. up to 0.03% – Ret. above 0.03%	St. I.
Cadmium	– N	– N	– N	I.
Calcium	– St. Pro.	– Pro.	– Pro.	
Carbon	– St. Pro.	– Pro.	– Pro.	
Cerium (& Lanthanum)	– St. Ret. after S down to 0.015% or less	– Ret.	– Ret. (Note 1)	
Chromium	– Ret	– St. Ret. (>0.05%)	– St. Ret.(>0.05%)	
Cobalt	– W. Pro.	– W. Pro.	– W. Pro.	Sl. I.
Copper	– W. Pro.	– W. Pro.	– W. Pro.	I.
Hydrogen	– St. Ret.	– Ret.	– Ret.	D.
Gold	– U	– N. or W. Pro.	– N. or W. Pro.	
Lead	– U	– N. up to 0.7	– N. up to 0.7	N.
Lithium	– U	– U. (Note 1)	– U. (Note 1)	
Magnesium	– Ret.	– Ret. if over 0.1% (Note 1)	– Ret. if over 0.1% (Note 1)	W. D.
Manganese	– N.	– W. Ret. (Note 2)	– St. Ret. (Note 2)	N.
Molybdenum	– Ret.	– Ret. (>0.1%)	– Ret. (>0.1%)	D.

Table 4. EFFECT OF ELEMENTS ON THE GRAPHITIZATION OF MALLEABLE IRONS (Continued)

Element	*Primary Graphitization (Mottling)*	*Secondary Graphitization*		*Nodule Count.*
		First Stage	*Second Stage*	
Nickel	— Pro.	— Pro.	— Pro.	W. I.
Nitrogen	— Ret.	— Ret.	— Ret.	D.
Phosphorus	— Pro.	— Ret.[79]	— Ret.[79]	I.
Selenium	— St. Ret. (>0.001%)	— Ret. if over 0.15%	— Ret. if over 0.15%	
Silicon	— St. Pro.	— St. Pro.	— Pro.	St. I.
Sodium	— U.	— Pro.	— Pro.	I. (<0.12%)
Sulfur	— Ret. (Note 2)	— Ret. (Note 2)	— St. Ret. (Note 2)	D. (<0.2%)
Tellurium	— St. Ret. (>0.001%)	— Ret. if over 0.15%	— Ret.	
Tin	— U	— N. up to 0.05%	— W. Pro. <0.015% Ret. over 0.02%	N.
Titanium	— St. Pro.	— Pro. up to 0.15%	— Pro. up to 0.01%	
		— St. Ret. over 0.15%	— W. Ret. over 0.02%	I.
Uranium	— St. Pro.	— St. Pro.	— St. Pro.	
Vanadium	— Ret.	— St. Ret.	— St. Ret.	D. > 0.2%
Wolfram (Columbium)	— N	N. or W. Ret.	— N. or W. Ret.	D. > 0.3%
Zinc	— U	St. Ret.	— St. Ret.	St. I.
Zirconium	— St. Pro.	St. Pro. over 0.02%[221]	— St. Pro. over 0.02%[220]	
		St. Ret. up to 0.15%[222]	— N.[222]	I.

Legend:
N—Negligible effect.
Pro.—Promotes graphitization.
Ret.—Retards graphitization.
St.—Strongly.
U.—Direct effect unevaluated.
W.—Weakly.
I.—Increases.
D.—Decreases.

Note 1: Desulfurizes, leaving excess manganese to exert influence.

Note 2: When Mn/S ratio is unbalanced.

TABLE 5. PROCESSING FACTORS AFFECTING MALLEABLE IRON GRAPHITIZATION

Factor	Primary Graphitization (Mottling)	Secondary Graphitization First Stage	Second S
Highly graphitic materials in charge	Pro.	—	—
Highly oxidized or rusty materials in charge	Ret.	Ret.	Ret.
Melting Atmospheres containing:			
Oxygen	Ret.	Pro.	Pro.
Nitrogen	Ret.	Pro.	Pro.
Carbon Monoxide	Pro.	Ret.	Ret.
Water Vapor	Ret.	—	—
Deoxidation of Melt	Pro.	Pro.	Pro.
High melt superheat	Ret.	—	—
Fine grain size or decreasing casting section thickness (high solidification rate)	Ret.	Pro.	Pro.
Heat-treating furnace atmosphere high in:			
Hydrogen	—	St. Ret.	St. Ret.
Carbon Monoxide	—	Neg.	Ret.
Water Vapor	—	Ret.	Ret.
Nitrogen	—	Neg.	Neg.
Prebake or slow rate of heating to first-stage	—	Pro.	Pro.
High first-stage temp.	—	Pro.	Ret.

Legend:

Neg.—Negligible
Ret.—Retards graphitization
Pro.—Promotes graphitization
St.—Strongly

TABLE 6. TRAMP ELEMENTS FOUND IN U.S. PIG IRON[221]

Element	*Symbol*	*Quantity (%)*
Aluminum	Al	0.002 –0.03
Boron	B	<0.0001–0.03
Cadmium	Cd	<0.001 –0.005
Chromium	Cr	0.01 –0.05
Cobalt	Co	<0.005 –0.02
Copper	Cu	0.001 –0.2
Lead	Pb	<0.001
Magnesium	Mg	<0.001 –0.02
Molybdenum	Mo	0.004 –0.02
Nickel	Ni	0.005 –0.1
Tin	Sn	<0.005 –0.01
Titanium	Ti	0.001 –0.3
Vanadium	V	0.004 –0.03
Zirconium	Zr	<0.005 –0.01

ing soundness, and the direction and rate of both primary and secondary graphitization. High carbon monoxide and carbon dioxide promote mottling (i.e., primary graphitization) and hence favor the thermodynamically stable system. High hydrogen, nitrogen, and water vapor will direct eutectic freezing toward the metastable system. Malleablization is favored by high carbon monoxide in the melting furnace atmosphere, but is retarded by nitrogen. It is very difficult to obtain a permanent increase in the oxygen content of malleable irons. Raising the oxygen from 15 to 110 ppm. has been shown to have no effect on the annealability of the iron.[262,263] Because oxygen treatments reduce the graphitizing influence of "deoxidizers" (e.g. aluminum, titanium), oxygen is sometimes mistakenly considered to be a carbide stabilizer. Water vapor as such apparently has no effect, unless it breaks down into its constituent elements. Dissociated water vapor effectively suppresses mottling tendency, but it is detrimental to second-stage graphitization.[277] As the factors involved are too numerous and complex to discuss here, it is suggested that for further information reference be made to the published literature.[160,161,162,47,232,278]

The amounts and relative proportions of gases in heat-treating atmospheres affect the surface oxidation, decarburization, and annealing rates of malleable iron castings. The net effect of these phenomena is found in the appearance, mechanical properties, and machinability of the metal. More detailed coverage of the complex gas reactions inherent in the process may be found in the articles covered by the bibliographical references.[155,156,17,157,178,179,180,181,182]

MELTING AND REFINING REACTIONS

Before passing on to a consideration of the heat-treatment of malleable irons, it would be well to pause momentarily to note a few of the fundamental phenomena transpiring during the melting and refining processes.

The prime purpose of a cupola obviously is to melt the iron and alloys charged. The necessary heat is generated largely through the following two exothermic reactions:

$$C + O_2 = CO_2 + 175{,}900 \text{ Btu.}$$
$$CO + \tfrac{1}{2}O_2 = CO_2 + 122{,}100 \text{ Btu.}$$

This heat is dissipated by:

(a) absorption by the metal charged,

(b) absorption and condution through the furnace refractories,

(c) absorption by ingredients of the charge other than the iron itself (e.g. coke, ferroalloys, flux);

sample reaction: $CaCO_3 + 76{,}500 \text{ Btu} - CaO + CO_2$

(d) absorption by the air blast,

(e) vaporization of moisture contained in the blast and by

$$C + H_2O + 57{,}800 \text{ Btu} = CO + H_2;$$

(f) *loss out the top of the stack (conduction and convection) or by absorption by a heat exchanger,*

(g) absorption by the coke bed reaction,

$$C + CO_2 + 58{,}700 \text{ Btu} = 2CO$$

(h) formation of slag.

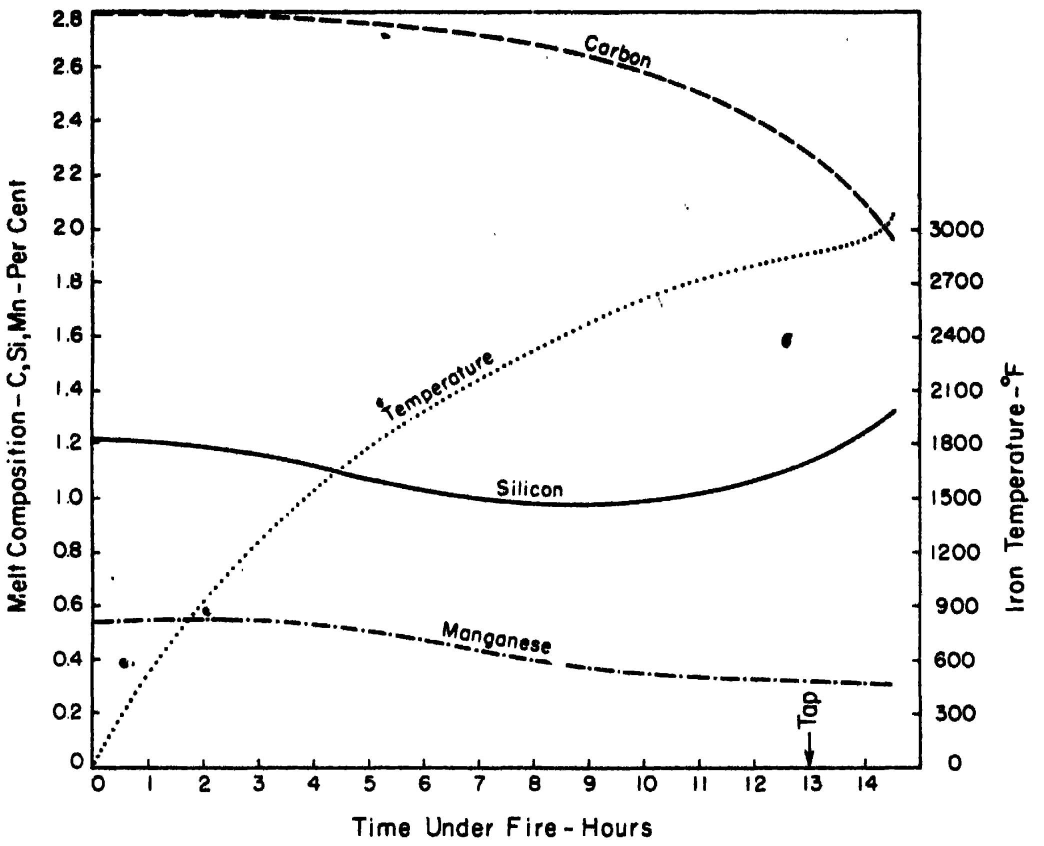


Fig. 25. **Changes in composition occurring in carbon, silicon, and manganese contents during the progress of a production air furnace heat.**

Other reactions would include some of the following:

(1) Pickup of sulfur from the fuel by the iron, especially just prior to the time when the iron melts.

(2) Pickup of carbon by the iron in the melting zone, according to the reaction, $3Fe + 2CO = Fe_3C + CO_2 + 79{,}560$ Btu, or by direct solution of the carbon in iron, $3Fe + C = Fe_3C$. The higher the CO_2 in the atmosphere (indicative of efficient combustion) the lower will be the carbon pickup.

(3) Oxidation of metallics (Fe, Si, Mn) by CO_2, by oxygen, if present, and by metallic oxides.

e.g. $Si + 2FeO = SiO_2 + 2Fe$.

(4) Reaction of metal oxides with refractories.

(5) Reaction of flux with silica in refractories or in ash from coke.

$$CaO + SiO_2 = CaSiO_3 \text{ (slag)} + 37{,}800 \text{ Btu}.$$

(6) Desulfurization:

$$\mathrm{FeS\ (MnS) + CaO = CaS + FeO\ (MnO)}$$

$$\mathrm{2CaO + 3FeS + CaC_2 = 3CaS + 3Fe + 2CO}$$

It is quite apparent from the foregoing that the chemical reactions in the cupola are very complex, and space in a book of this type does not permit further consideration. Complete information is available in the several texts on the subject.[111,230]

In the air furnace the burning of pulverized coal or oil generates heat which is transmitted to the metal by convection, by conduction, and by radiation. Since intimate contact of the heat source with each piece of the charge is non-existent, the efficiency of the air furnace as a melting unit is much lower than that of a cupola. On the other hand, since the metal and fuel are not thoroughly mixed in the air furnace, pickup of carbon and sulfur from the fuel can be minimized or avoided. The electric furnace presents a situation similar to the air furnace. Most of the heat is transferred to the metal by radiation arising either directly from the arc or indirectly via the incandescent refractory lining.

In batch melting there is usually an excess of CO_2 or O_2 in the furnace atmosphere. These gases form the iron oxide Fe_3O_4 on the surface of the charge as it is being heated. Above about 1290 degrees F. either FeO or Fe_3O_4 will be formed, depending upon the CO content of the gases. These oxides react with the furnace refractories to create a liquid silicate slag, which in turn reacts with liquid metal to convert carbon to CO, silicon to SiO_2, and manganese to MnO. The CO bubbles through the slag and burns off; the SiO_2 and MnO enter the slag. It is in this way that carbon, silicon and manganese, as well as iron itself, are eliminated from the melt. If the slag is left over the molten bath, the reactions fall off and heat transfer to the melt is poor. Thus, it behooves the air-furnace melter to clean off his bath at the earliest possible time after melt-down to obtain maximum temperatures and refinement of the iron.

Manganese is oxidized at a decreasing rate as the temperature of the bath increases; at very high temperatures the loss becomes greatly reduced because of the protective action of carbon. The rate of carbon loss from the melt is not significant below about 2550 degrees F.,[231] but it increases as the temperature rises; this loss is the sum of direct oxidation at the surface of the melt and silica reduction ($2C + SiO_2 = 2CO + Si$). The latter reaction becomes important particularly at temperatures of superheat above about 2700 degrees F., at which temperature the reaction is approximately in equilibrium. In other words, silicon loss occurs at low bath temperatures, but with high superheat temperatures the silicon content actually rises because of silica reduction. Typical changes that take place in the chemistry of a heat (cold-melt) are represented graphically in Fig. 25. To check the progress of refining in the cold-melt air or electric furnace or in the secondary unit of a duplex operation, the malleable melter periodically pours test plugs or blocks, which correspond in cross-section to the heavier line of castings made in his particular shop. A series of such plugs, 2 inches in diameter and cast from a batch air-furnace operation, is illustrated in Fig. 26. These show how, through carbon reduction and superheating, the mottling tendency of the iron is progressively diminished and finally eliminated, resulting in a fully white iron structure.

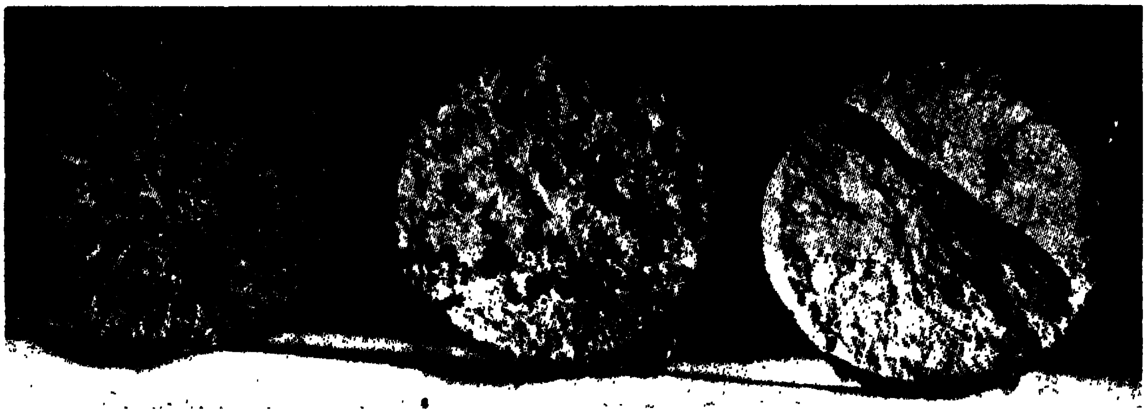


Fig. 26. Photographs of mottle test blocks poured as the heat progresses. The transition from a gray through a mottled to a complete white fracture is clearly indicated.

In addition to the references cited above in the discussion of the effect of gases on graphitization, many excellent papers have been reported in the trade journals which delve into the melting processes and their effect on properties in far greater detail than is possible here.[233-249 incl.]

THE MALLEABLIZING PROCESS

It was shown in the discussion of the freezing of white iron that when a mold has been filled with an iron of malleable composition, the iron will freeze with all of its carbon combined as cementite or iron carbide, and after cooling to room temperature it will consist of massive carbides and pearlite (ferrite and cementite in alternate layers). The purpose of malleablization is to convert all of the combined carbon into elemental carbon (graphite) and ferrite. In commercial practice this process is carried out in two steps, commonly referred to as the first and second stages of the anneal.

First-Stage Malleablization

When white iron castings are heated up through the eutectoid range, often called the "critical" range, the pearlite transforms into austenite by a process of rapid diffusion of the carbon from cementite into the iron to form a solid solution of carbon in gamma iron. The massive carbides are virtually unaffected by heating. Therefore, above the critical range (but below the eutectic) the iron consists of massive carbides in austenite. These changes are schematically indicated on the right side of Fig. 15.

When white iron castings of malleable composition are held at elevated temperatures, particularly those above the eutectoid or critical range, graphitization of the massive carbides will occur. The reaction

$$Fe_3C \rightleftharpoons 3Fe \text{ (austenite)} + C \text{ (graphite)}$$

proceeds to the right. As with most chemical reactions, the higher the temperature the faster the process. Also, the solubility of carbon is increased with greater temperatures. Extremely high temperatures in this range of gamma iron are commercially impractical, however, because of (a) very low hot strength in the castings at such temperatures (and resulting distortion), (b) higher refractory requirements, (c) greater fuel consumption, and (d) inferior mechanical properties in the final product. Hence, a first-stage holding temperature is ordinarily selected somewhere between 1550 and 1800 degrees F., this depending for the most part on the type of heat-treating equipment available at any particular plant.

The temperatures employed for malleablization are sufficiently high to induce extensive scaling and decarburization if the castings are left exposed to normal room atmospheres during the treatment. Therefore preventive steps are taken in commercial practice by sealing the hot castings from the air or by surrounding them with a controlled artificial atmosphere that will minimize or eliminate scaling and decarburization. The work may be sealed through packing the castings in closed pots mudded with fireclay. In air-tight muffle furnaces an atmosphere which precludes oxidation of the iron and its constituents is soon generated through slight surface decarburization during the initial heating cycle. In batch annealing this means is generally preferable to sealing each container of castings, since handling is reduced, faster cycles are possible, and cleaner working conditions prevail. Artificial atmospheres, produced by an external generator, are employed particularly in continuous malleablizing furnaces. Such atmospheres maintain a minimum of oxygen, carbon dioxide, and water vapor, which are oxidizing to the iron.

Figure 6 shows that the austenite of the metastable system can dissolve somewhat more carbon than can the austenite of the stable system. Since white iron has solidified metastably, a pressure exists for the carbon to precipitate out of the austenite as free graphite, this crystallization originating at the austenite-cementite interface. When white iron is reheated for first-stage graphitization, the initial rejection of a minute carbon spot depletes the austenite of carbon, and so more is dissolved from the adjacent cementite, leading to further carbon deposition on the original graphite nucleus (Fig. 15). Thus, first-stage graphitization consists of four simultaneous processes; (1) solution of the cementite at its interface with austenite, ((2) dissociation of dissolved cementite into its constituent elements (iron and carbon), (3) migration of the carbon atoms through the austenite lattice or diffusion of matrix atoms away from the nuclei on which the temper carbon grows, and (4) precipitation of carbon as graphite.[158 183,201]

Holding white iron castings at first stage malleablizing temperature enables these reactions to continue until all massive carbides have been decomposed; i.e., until equilibrium is achieved for that temperature. The structure then consists of graphite, or "temper carbon nodules," distributed throughout the matrix of austenite, which is now a solid solution of gamma iron saturated with an amount of carbon predicated on the particular holding temperature. At this point, first-stage graphitization is considered to be complete, for no further reactions will take place unless the temperature is changed.

For rapid anneability it is desirable to have a relatively large number of graphite nodules per unit volume, since this condition reduces the distance through which the carbon atoms have to migrate in the austenite to get from the cementite to the nearest carbon spot. While the precise mode of graphite nucleation appears to be quite complex and is still very obscure, a number of means are available for increasing the nodule count:

(1) Obtain a fine dispersion of the massive carbides in the white iron by cooling rapidly after pouring off the mold. The rate of cooling of highly chilled or very thin isolated sections in a green sand mold naturally brings about a fine carbide distribution.

(2) Prebake for a few hours between 650 and 800 degrees F. before heating to first-stage temperature.[184,185] Further nucleation has been found to result from heating, after this low temperature prebake, to 1200 degrees F. for a brief time and then cooling to room temperature before proceeding with the regular malleablization cycle. The benefit of copper contents in this connection was discussed earlier.

(3) Use an initially high first-stage temperature. While such high temperatures will increase the number of nodules, if the temperature is maintained for any length of time the graphite becomes sprawly and elongated and, if held just under the eutectic will approach the typical flake graphite form of gray iron.[186] These high temperatures are not conducive to good mechanical properties.

(4) Alloy or inoculate with graphitizers, such as silicon, aluminum, or boron.

(5) Prestress the white iron before malleablizing.[187]

(6) Control the melting furnace atmosphere so that it is highly reducing.[162]

(7) Pretreat the iron so as to have a martensitic matrix for malleablizing.[251] This may be achieved by heating the white iron to a high austenitizing temperature, followed by a drastic quench, all prior to the normal annealing cycle. This method

is not practiced commercially because of the nature of the quench and its tendency to cause cracks.

If after completion of first-stage malleablization the temperature is slowly lowered, more carbon precipitates out from austenite upon the existing nodules. This phenomenon is due to the lower solubility of carbon in austenite at temperatures approaching the eutectoid, as can be readily visualized by reference to the constitution diagram of Fig. 6.

SECOND-STAGE MALLEABLIZATION

When the temperature of the iron has been reduced enough so that it falls into the critical (eutectoid) range, three phases coexist; austenite-ferrite-cementite (metastable), or austenite-ferrite-graphite (stable). Because of the very low solubility of carbon in austenite in this range, during a slow rate of cooling through this range graphitization proceeds (in accordance with the stable system) at a rate about ten times that which held when the iron was at a temperature immediately above the range.[188] However, if the rate of cooling is so fast that graphitization cannot go to completion, the reaction will proceed metastably and cementite will be rejected in the form of pearlite. At a temperature only slightly below the critical range, this pearlite will eventually graphitize, but at an extremely slow rate, about one-hundredth the rate within the range. This fact can be explained on the basis of the very limited solubility of carbon in ferrite, the slow diffusion rates in ferrite, and the very slight difference between ferrite saturated toward graphite and ferrite saturated toward cementite. It is obvious that for minimum malleablizing time a uniform slow cool through the critical range is very helpful as long as the cooling rate is slow enough to give a completely graphitized product by the time the castings have passed down through the lower critical temperature. This type of cycle is preferable to a faster rate of cooling through the range followed by a long sub-critical hold. The actual temperature boundaries of the range will vary, of course, with composition and cooling data.

Since the carbon in austenite near graphite nodules has shorter distances through which to diffuse than has carbon farther from the nodules, graphitization in the critical zone is faster in the vicinity of the nodules. Therefore, if the cooling rate through the range has been too fast, the areas surrounding the nodules will be completely graphitized, while those at greater distances from the nodules will be pearlitic (Fig. 27). Because of its general appearance, this is frequently referred to as a "bull's eye" structure.

In the event that the rate of cooling through the range has not been quite slow enough, or the holding time in the range not long enough, some traces of pearlite may exist at or just beneath the surface of the casting. The pearlite is located there because there are fewer

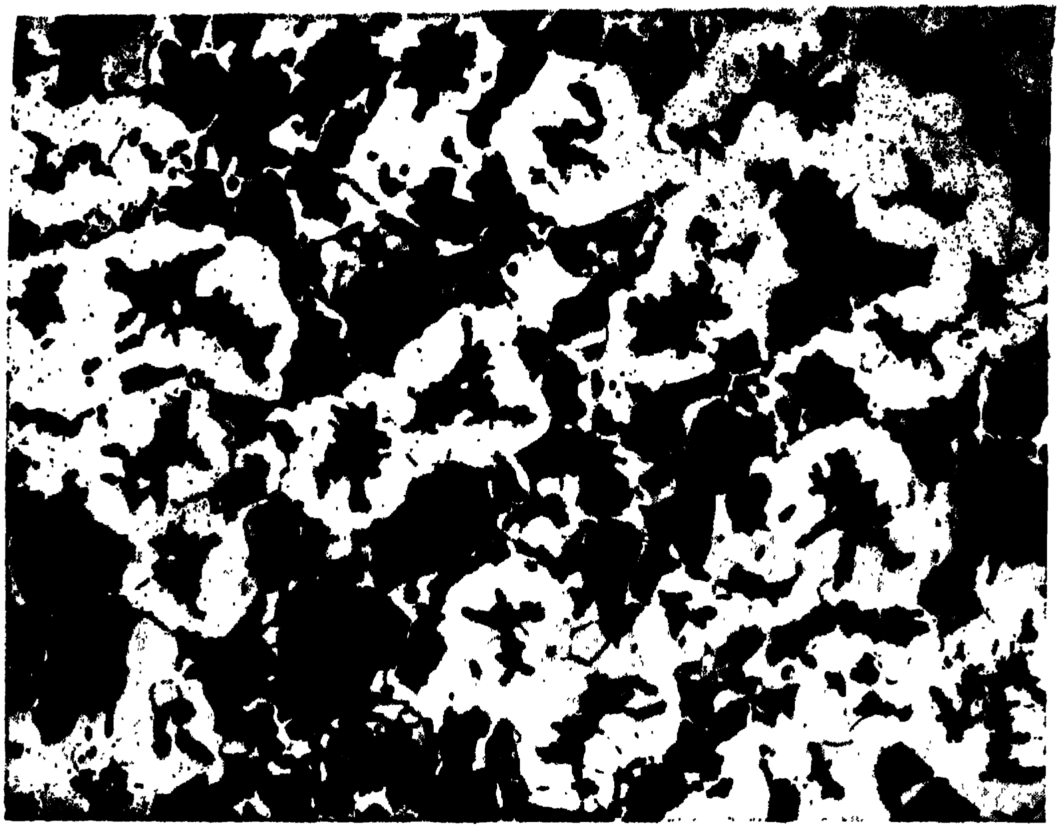


Fig. 27. Typical appearance of a "bull's eye" structure. Its characteristics are a temper carbon nodule surrounded by a ferritic area, with lamellar pearlite located between the bull's eyes. Nital etch, magnification 100 X.

carbon nodules in this region, and the carbon atoms hence must migrate greater distances in order to precipitate on the nearest nodules deeper within the casting (cf. Fig. 28). The lower nodule count at the periphery is due to decarburization in the anneal and also the lower initial carbon content there in the as-cast condition.[191] Some theory exists that the silicon on the surface is not free to act as a graphitizer, being tied up as silicon hydride.

Once an iron has been fully graphitized on slow passage through the critical temperature zone, no further structural changes take place at lower temperatures. Therefore, cooling to room temperature may be at any rate that is feasible with the particular heat-treating equipment involved. As was mentioned earlier in this chapter, a fairly rapid cool from 1150 degrees F. or higher is desirable in order to offset any embrittling tendency that might be produced by too slow a cool through the "blue heat" range (1100-400 degrees F.) or by a subsequent galvanizing treatment. In large loads the cooling of heavy-sectioned or tightly-packed castings tends to lag behind that of the castings on the outside of the load. Unless actual temperatures of all the castings in the malleablizing furnace can be under rigid control, it is customary practice to continue the slow cool well below the critical range in order to be certain that all castings in the load will have had ample time in

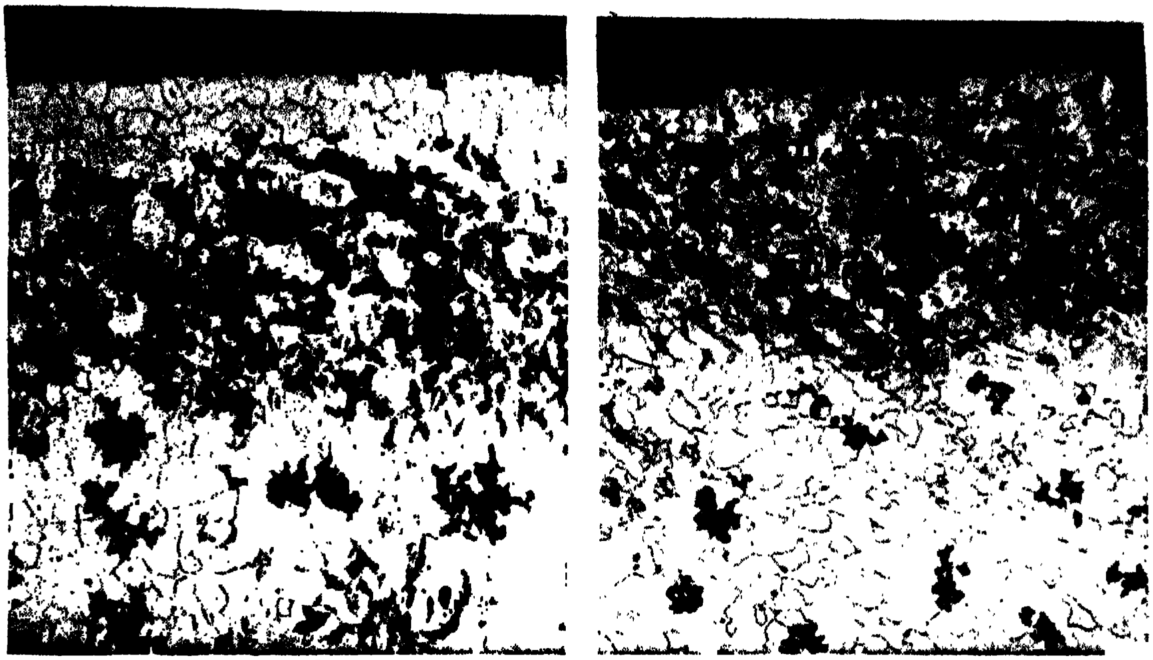


Fig. 28. **Photomicrographs indicating two types of pearlitic rims. The left-hand picture shows a pearlitic rim of approximately 0.018 inches thickness underlying a ferritic skin of approximately 0.007 inches thickness. On the right is shown a continuous pearlitic rim, i.e., without the ferritic skin. This structure usually indicates an excessively reducing atmosphere. Nital etch, magnification 100 X both left and right.**

the range to graphitize completely before cooling more rapidly to room temperature.

To summarize, the malleablization process occurs essentially in two steps: (1) First-stage in the "gamma" range, in which all massive carbides are broken down and equilibrium is established between iron and carbon for the particular holding temperature employed. (2) Second-stage within or just below the eutectoid or "critical" temperature range, the last few hundredths of one per cent of carbon remaining in solution in the austenite (or ferrite) are precipitated as graphite on the nodules formed during the first stage.

During solidification all of the carbon in the melt is intentionally tied up chemically as iron carbide or cementite. Malleablization releases this carbon in its entirety from the carbide, permitting it to precipitate out of solution as compact graphite agglomerates and leaving a tough ferritic matrix. The process also serves to homogenize the structure and to render the iron completely free from casting stresses.

PEARLITIC MALLEABLE IRONS

The role of carbon in standard malleable iron has been discussed. To review briefly: —In molten iron carbon furnishes high fluidity, making it possible to cast thin and intricate shapes into final form. So as to assure excellent properties in the final product, none of this carbon is permitted to come out as flake graphite during solidification. Instead, it is retained as iron carbide, which, because of its hardness and brittleness, must be subsequently converted by the malleablizing process into its basic compounds—ferrite and temper carbon. In the form of compact nodules, the graphite offers but little discontinuity to the tough ferritic matrix. Furthermore, the graphite nodules serve the very beneficial purpose of lubricating cutting tools, a fact which accounts considerably for the extraordinarily high machinability of malleable iron.

Carbon can be made to contribute additional unique properties to malleable iron if a small controlled quantity (e.g. 0.3 per cent to 0.9 per cent) is retained as finely distributed iron carbide in the matrix. By virtue of the high strength and hardness of the carbide itself, the over-all strength and hardness of the castings may be increased over those of standard (ferritic) malleable iron to a degree roughly proportional to the amount of combined carbon remaining in the finished casting. Malleable iron that contains purposely retained eutectoidal carbides or low-temperature transformation products is called pearlitic malleable iron, or often just pearlitic malleable.

The nature of the carbides and their abundance, size, and distribution directly affect the properties of the material. If, through quenching, the initial matrix is martensitic (cf. Fig. 29), the iron will have very high hardness (e.g. 550+ BHN). Upon tempering at a relatively low temperature (e.g. 800 or 900 degrees F.) the martensite will transform into a matrix like that shown in Fig. 30. Such an iron will have very

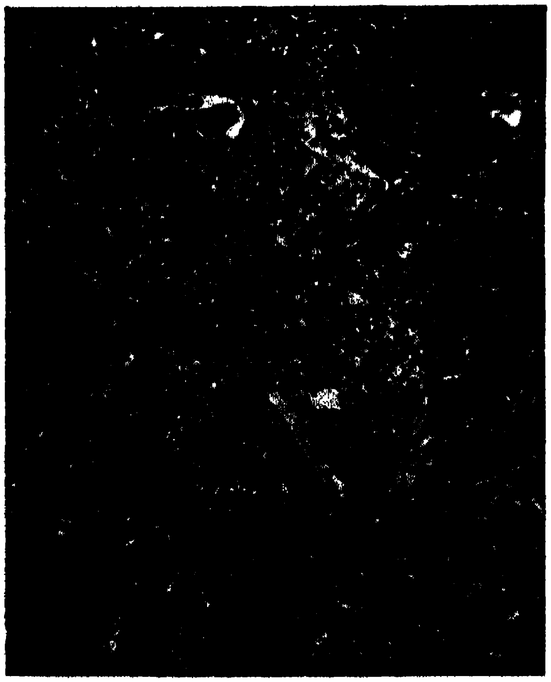


Fig. 29. Martensite in malleable iron which was oil quenched from the austenitizing temperature and tempered at 400° F. This structure had a hardness of Rockwell C 48 (461 BHN). Nital etch, magnification 100 ×.

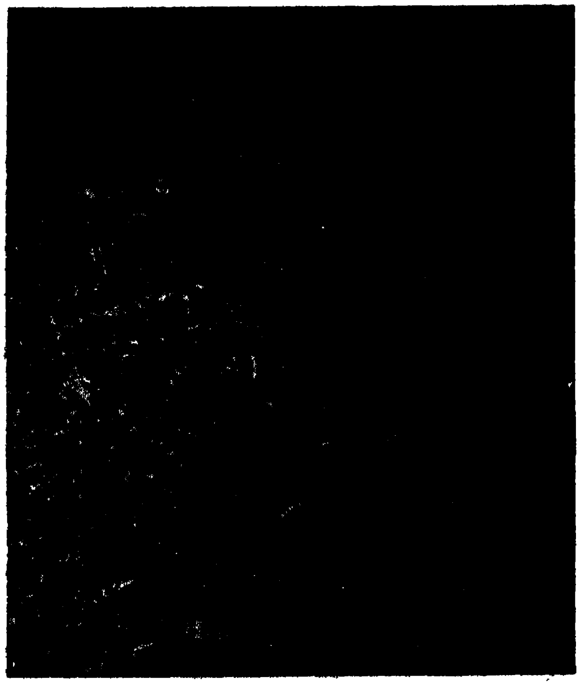


Fig. 30. Tempered martensite in pearlitic malleable iron. After completion of the first stage graphitization, castings were air quenched and tempered. The resulting hardness was 255 BHN. (Process II), Nital etch, magnification 500 ×.

high strength (e.g. 125,000 psi. tensile and 110,000 psi. yield), hardness (e.g. 300 BHN) and wear resistance, but its ductility, machinability, and impact resistance will be below that of pearlitic malleable irons treated at higher tempering temperatures. On the other hand, if the carbides are spheroidal in shape and uniformly distributed (Fig. 31), the iron will have better ductility and machinability than a laminar pearlitic malleable at a comparable hardness level. Matrices consisting of a dense pattern of finely spheroidized cementite will respond most rapidly to hardening treatments[89,189,190] which are more fully covered in the last section of this chapter.

In general, the properties of a particular pearlitic malleable iron are dependent upon (a) the chemistry and processing of the base iron from which it is made, (b) the presence of added alloys, (c) the ability of the heat-treating equipment to obtain and accurately maintain the desired temperatures, and (d) the heat-treating cycle itself. To elucidate, a high silicon content will hasten first-stage graphitization, but will render the iron more sensitive to slight changes in the tempering cycle. White irons that are low in total carbon generally produce pearlitic malleables of somewhat higher ductility than will the irons of high carbon content. White irons melted under severely oxidizing conditions will usually have a low nodule count, and so a longer first-stage graphitizing cycle will be necessary. Very high nodule counts in unalloyed pearlitic malleable irons tend toward non-uniform response to tempering. Chemical elements may be added to the molten base irons for such purposes as controlling the shape, compactness, and distribution of the temper carbon nodules, permitting heavier mottle-free sections to be cast, hastening first-stage

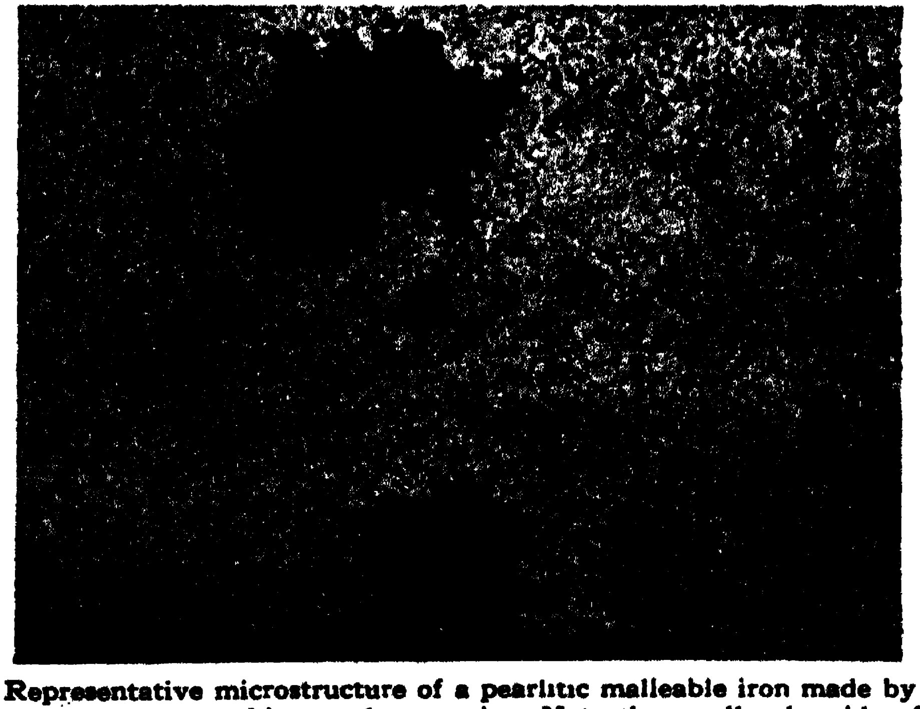


Fig. 31. Representative microstructure of a pearlitic malleable iron made by alloying with manganese, air quenching, and tempering. Note the small spheroids of carbide in the matrix. Nital etch, magnification 500 ×.

graphitization, strengthening the matrix, facilitating the heat-treatment, providing better resistance to corrosion, diminishing or eliminating the susceptibility to temper embrittlement, increasing hardenability, affording structural stability to elevated-temperature service conditions, retarding graphitization during tempering, or a combination of these. The type of heat-treating equipment available may decide the method of making pearlitic malleable iron. For example, a plant having only large batch type ovens would probably employ alloying, since it would be impossible to obtain uniform air quench of a load of several tons of unalloyed iron and liquid quenching would not be feasible. A company whose pearlitic malleable production is only a small proportion of the total malleable output would probably employ small furnaces, which would lend flexability to the installation without huge capital investment.

Because of differences in base iron, in the nature of the castings made, in the volume of production, in existing heat-treating facilities, and in properties required of the castings, there are probably no two plants that manufacture pearlitic malleable iron in precisely the same way. However, all the various methods for producing pearlitic malleable castings, whether from white iron of standard malleable composition or from alloyed iron, have one requirement in common, namely, that the massive (or primary) carbides be completely eliminated. This is merely another way of saying that completion of first-stage graphitization is a prerequisite for all ways of manufacturing pearlitic malleable castings. Table 7 is a breakdown of the several common practices in commercial usage. Each of the six possible steps in the heat-treatment of pearlitic malleable iron is reviewed below, followed by a discussion of each of the eight processing methods listed in Table 7.

First-Stage Graphitization. As stated above, all white irons destined to become pearlitic malleable castings are heated to a high enough temperature within the austenitic range and held sufficiently long at that temperature for all massive carbides to decompose (i.e. graphitize) and for equilibrium to prevail. The cycle is essentially the same as the first-stage of a full malleablizing treatment. Irons alloyed with certain elements or combinations of elements may require a somewhat extended cycle to complete graphitization.

Second-stage Cycle. If the iron is to be fully malleablized before conversion into pearlitic malleable, it must be put through a complete second-stage cycle. This is common practice for plants which may require only small or moderate tonnages of pearlitic malleable made to a number of different specifications. In such plants all castings are initially given the same full malleablizing anneal, resulting in a wholly ferritic material. Then only those castings that are to be transformed into pearlitic malleable are reheat-treated in a short special cycle that will develop the desired recombination of carbon. Other plants which have appropriately

TABLE 7—COMMERCIAL PROCESSES FOR PRODUCING PEARLITIC MALLEABLE IRON

METHOD	UNALLOYED					ALLOYED		
	Quenched and Tempered			Reheat-treated Malleable Iron		Quenched and Tempered		Furnace Cooled
	Air Quench	Liquid Quench		Air Quench	Liquid Quench	Air Quench	Oil Quench	Mall. Cycle
Process Designation	I	II	III	IV	V	VI	VII	VIII
First Stage Graphitization	X	X	X	X	X	X	X	X
Normal Second-Stage Cycle				X	X			X
Air Quench from 1500° F. or higher	X	X		X		X	X	
Reheat into Austenitic Range.		X		X	X		X	
Liquid Quench from 1450° F. or higher		X	X		X		X	
Temper 450-1350° F.	X	X	X		X	X	X	
Matrix	Lamellar Pearlite and/or Spheroidite	Martensite, Tempered Martensite, or Fine Spheroidite		Lamellar Pearlite	Martensite, Tempered Martensite or Fine Spheroidite	Coarse Lamellar Pearlite and/or Spheroidite	Tempered Martensite or Fine Spheroidite	Coarse Lamellar Pearlite

alloyed their pearlitic malleable castings may process them right along with their standard malleable production in a normal annealing cycle. The alloying sufficiently retards second-stage graphitization in the treated castings so that the desired secondary carbides, usually in the form of laminar or partially-spheroidized pearlite, remain in the matrix of the finished product.

Air Quench. The air quench is an economical means for cooling castings fast enough through the eutectoid range to retain secondary carbides throughout the matrix. The quantity of pearlite so retained will depend upon the temperature at which the quench initiates and upon the rate at which the castings are cooled by the air. High quench temperatures and fast cooling rates result in greater amounts of retained carbide. An air blast directed on a thin layer of castings will produce high cooling of the work and consequently the retention of more and uniformly-distributed pearlite. On the other hand, a large load of castings brought out into still air will cool much more slowly because of the greater amount of heat that must be dissipated from the mass. In the work at the heart of the load and in heavy-sectioned castings there will be less total pearlite, and partial graphitization will develop ferritic areas immediately adjacent to the temper carbon nodules. Thus, the use of an air quench as the sole quenching medium for treating large batches of unalloyed castings is quite impractical. However, the air quench can be very satisfactorily incorporated in cycles of continuous furnaces that discharge only a few hundred pounds of castings each push.

Suitable alloying of irons to be air quenched will shift the T-T-T curve sufficiently to the right to assure a fully pearlitic matrix on air quenching even large loads of castings. This is illustrated by Fig. 32. After air quenching, alloyed irons not only possess a more uniform matrix, which is free from "bulls'-eyes," but they also have a finer carbide structure, which responds faster to subsequent tempering or spheroidizing treatments.

Reheating. Fully malleablized castings that are to be converted into pearlitic malleable have to be reheated to a high enough temperature above the lower eutectoid (A_{c1}) to dissolve a controlled quantity of carbon from the graphite nodules so that there will be sufficient combined carbon in the structure after subsequent quenching to develop the desired properties. The higher the temperature the faster will be the reaction and the greater will be the amount of carbon combined. However, excessively high reheat temperatures are generally avoided because of fuel economy, the greater need for protective atmospheres, and the increased possibility that quench cracks may develop, particularly if the subsequent quench rate is high. Accurate regulation of the time-temperature reheat cycle permits control of the carbon that is recombined. Reheating to some temperature within the eutectoid range for too short a time to

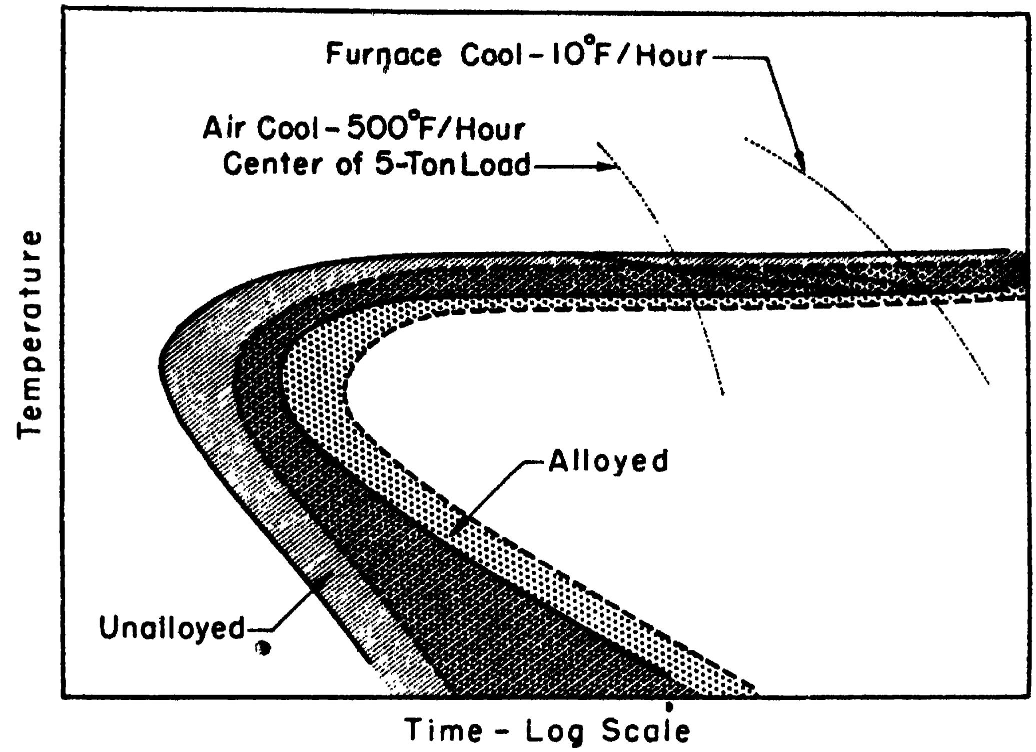


Fig. 32. **Time-temperature-transformation (T-T-T) curves for pearlitic malleable iron. Note that alloying shifts the curve to the right.**

effect homogenization results in carbon being combined only in the vicinity of the graphite nodules and at the grain boundaries. Figure 33 illustrates a pearlitic malleable, after tempering, that was made in this way. Castings to be subsequently air-quenched are generally reheated to a higer temperature than are those to be liquid quenched.

Liquid Quench. If a higher quenching rate than is possible by using an air-quench alone is desired, a liquid medium must be employed. Water and brine solutions are ordinarily too drastic, and so are seldom utilized for pearlitic malleable production. Through the addition of about one-half per cent carboxyl methylcellulose to water the quench rate is sufficiently retarded so as to approach that of the common mineral oils. Such a solution is non-toxic and presents no fire hazard, but it must be kept well agitated or the quenching results will not be uniform. Oils, having roughly one-third the quenching speed of water, are widely used by manufacturers of pearlitic malleable castings. The amount of martensite formed on quenching will depend on the quenching speed of the particular oil used, the temperature from which the work is quenched, the time at that temperature, the thickness of the castings, and the chemistry of the iron.

Liquid-quenching is widely utilized in the production of the very high strength and high hardness pearlitic malleable irons. Is also offers certain advantages over air quenching. A liquid-quenched matrix is uniform and very fine-grained, so it responds rapidly to tempering. Furthermore, at identical hardness levels, liquid-quenched pearlitic malleables

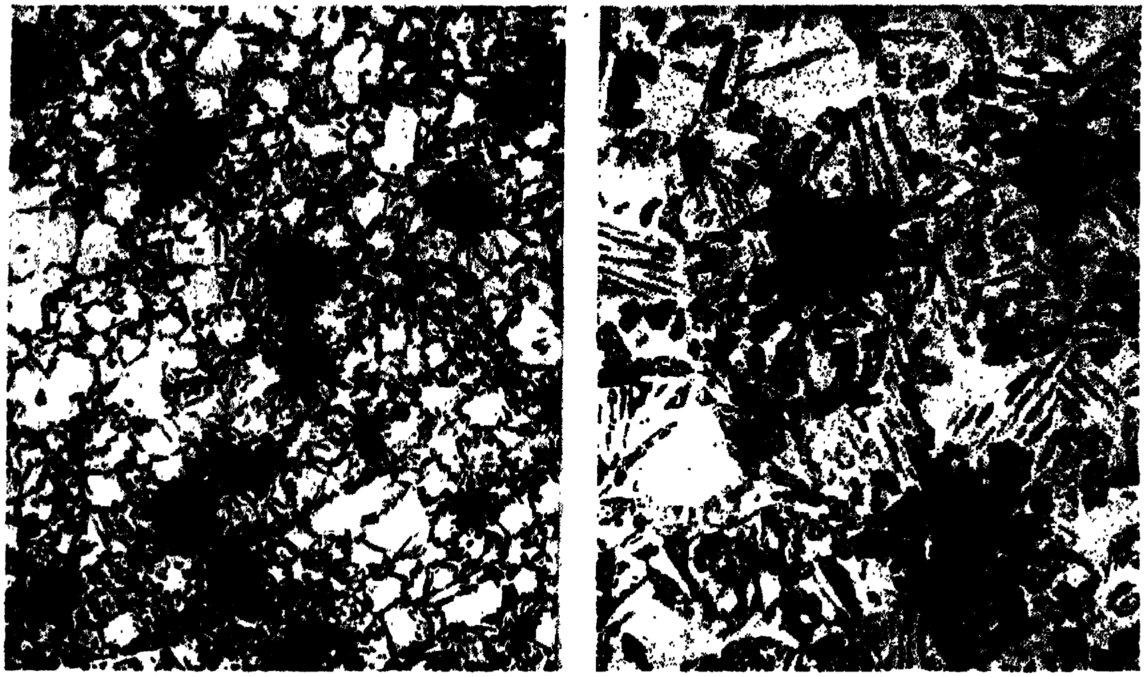


Fig. 33. Pearlitic malleable iron made by reheating fully ferritic malleable iron above the lower eutectoid temperature followed by liquid quenching and tempering. This particular structure results in properties that comply with ASTM Grade 45010. (Process V). The chemical composition of this iron was: total carbon—2.35%, silicon—1.04 %, manganese—0.42%, and sulfur—0.09%. Heat-treatment: 1¼ hours at 1510° F.—oil quenched and 20 minutes at 1200° F.—water quench. The mechanical properties of the base, ferritic malleable iron were: tensile strength—56,000 psi., yield strength—36,900 psi., and elongation in 2 inches—22.5%. The mechanical properties of the heat-treated pearlitic malleable iron were: tensile strength—80,700 psi., yield strength—61,000 psi., and elongation in 2 inches—10.1%. The hardness of the later was 201 BHN. Nital etch, magnification 150 × (left) and 500 × (right).

tend to have higher yield strengths than do irons produced by air quenching.[69,70,72] This is shown in Figure 34.

Isothermal quenching of malleable irons is quite feasible.[203,204,264] Fig. 35 illustrates the properties obtainable by isothermally quenching standard tensile test specimens from a 1600 degree F. austenitizing temperature into salt baths at various temperatures. As may be seen, the properties are dependent upon the temperature at which isothermal transformation occurs and on the presence of elements that increase hardenability.

Tempering. Except for those cases where high hardness is desirable and where low machinability and impact resistance are not objectionable, it is common practice to temper the air- or liquid-quenched irons. Those having coarse pearlitic structures (such as result from air cooling) are tempered at some relatively high temperature in the range of 1200 to 1320 degrees F., usually to bring about spheroidization or partial spheroidization of the pearlite. The time during which unalloyed castings are held at this temperature is fairly critical, because graphitization also occurs during tempering, so that some combined carbon is being removed.

Other factors which affect the tempering cycle are graphite distri-

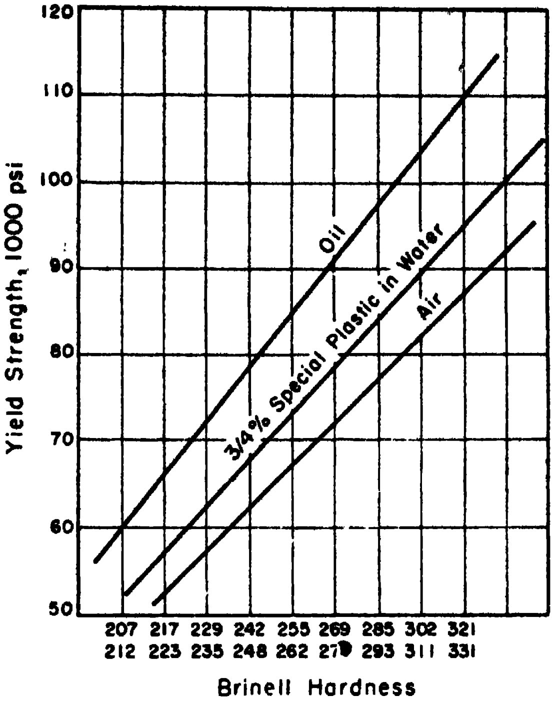


Fig. 34. **Relationship between yield strength and Brinell hardness as affected by quenching medium and rate.**

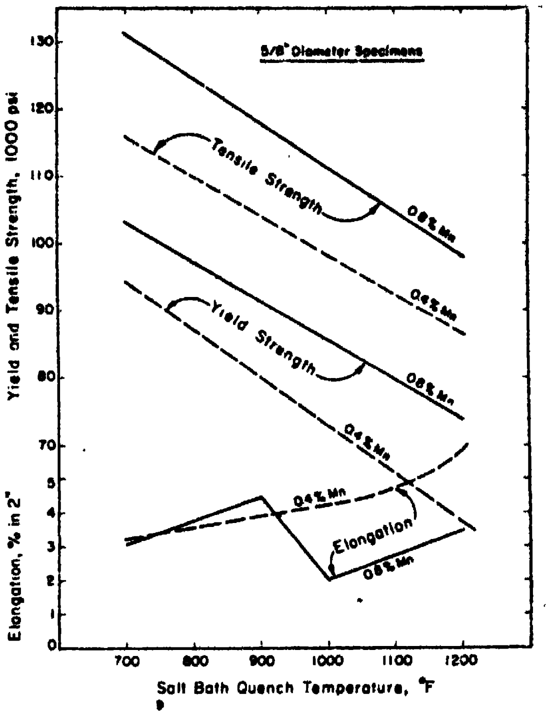


Fig. 35. **Typical mechanical properties obtained from standard malleable iron (dotted line) and pearlitic malleable iron (solid line) isothermally transformed at various sub-critical temperatures.**

bution, chemistry of the iron, and fineness of the as-quenched pearlite. For example, a high nodule count and high silicon content favor graphitization. On the other hand, certain carbide-stabilizing elements (e.g. manganese, molybdenum, sulfur) may be added for the purpose of permitting the spheroidizing reaction to predominate over graphitization, which can be held to a low or almost negligible level in this way. While somewhat longer tempering times are usually necessary to bring about spheroidization in alloyed irons, it is possible to treat loads of several tons and castings of widely different section thickness and still obtain greater uniformity of the pearlitic matrix than is possible with similarly-handled unalloyed work.

Irons that have been liquid-quenched to give a martensitic structure may be tempered at any temperature from about 450 degrees F. up to the lower eutectoid in order to develop a matrix of any of the tempered martensites or of spheroidite. Because of the high response of liquid-quenched irons to tempering, accurate control of the time-temperature cycle is imperative. Tempering at temperatures in the low side of this range will result in high-strength, high-hardness pearlitic malleable. The higher the draw temperature the softer the metal becomes and the more the properties approach those of the air-quenched pearlitic malleables. Fig. 36 shows this relationship. The effect of tempering on hardness is illustrated in Fig. 37 after holding oil-quenched pearlitic malleable iron for two hours at the indicated temperature.[206] Tempering rates are highest at the beginning of the cycle and fall off as the time is extended.[203]

PROCESSES OF PEARLITIC MALLEABLE PRODUCTION

UNALLOYED PEARLITIC MALLEABLE IRON

Unalloyed pearlitic malleable castings are made from white iron compositions that would ordinarily become standard (ferritic) malleable iron if put through a normal malleablizing anneal.

PROCESS I. (Air-quench and temper)

Considerable tonnages of pearlitic malleable irons are made by this method. The cycle is short and economical. It particularly lends itself to continuous heat-treating furnaces through which the castings pass in shallow trays or small containers. This permits frequent periodic discharge of small loads of a few hundred pounds each, thus assuring inti-

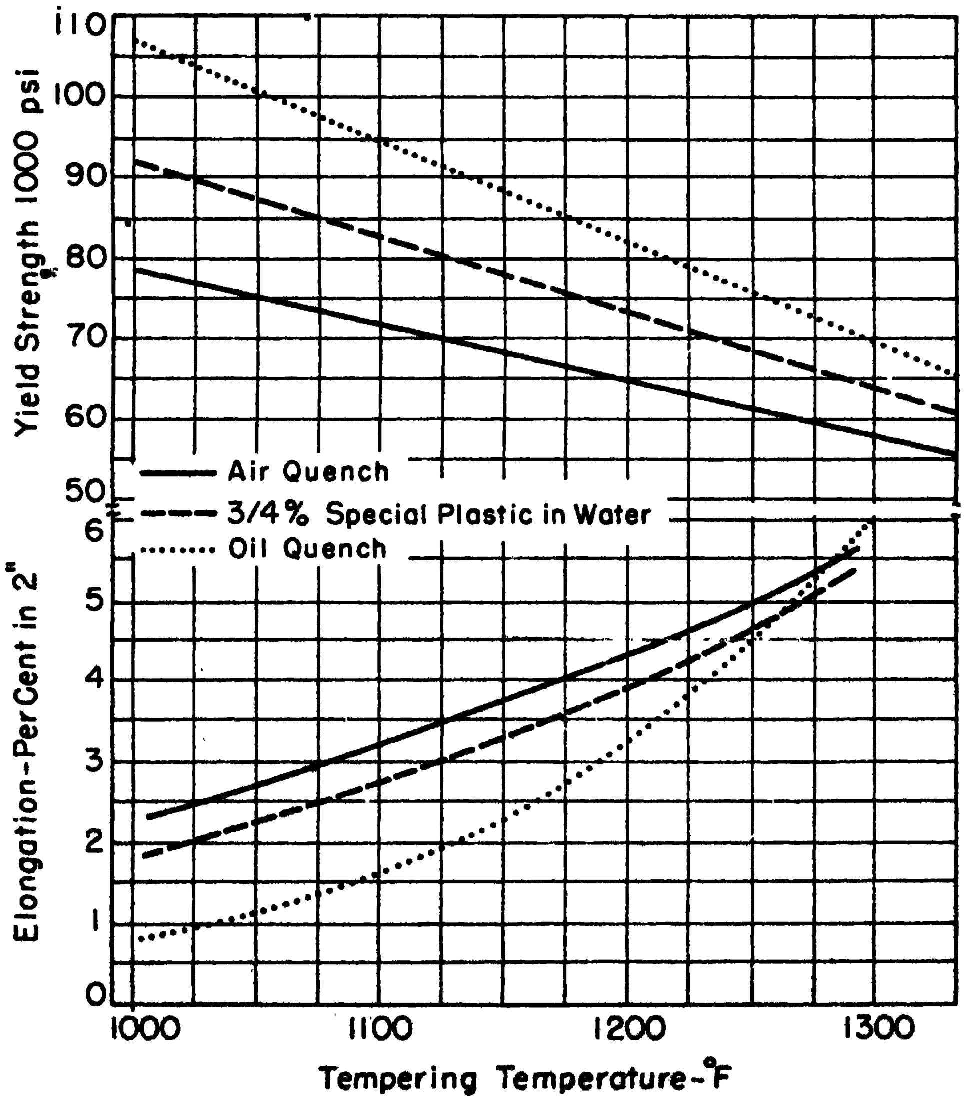


Fig. 36. Effect of tempering temperature on the mechanical properties of unalloyed pearlitic malleable irons quenched at different rates.

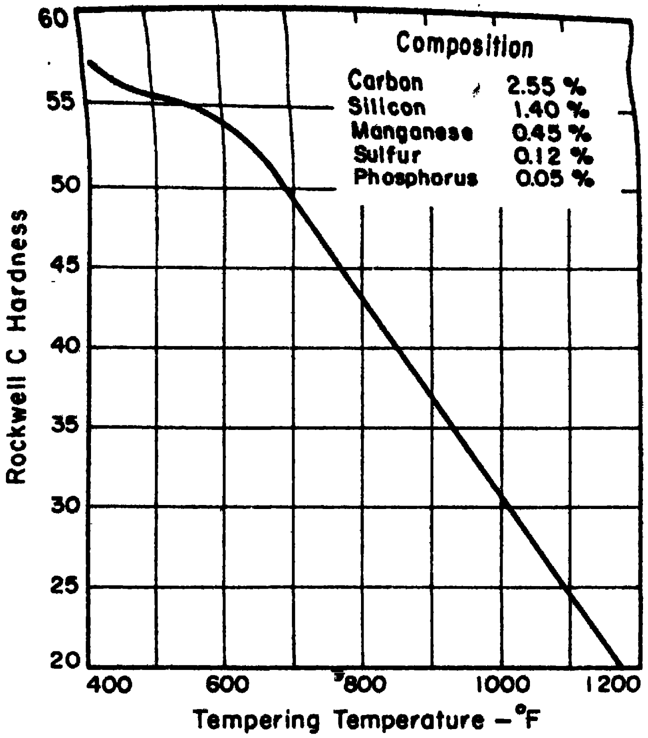


Fig. 37. Effect of tempering temperature on hardness of oil quenched pearlitic malleable iron. A one-half inch round was heated to 1600° F., held 30 minutes at that temperature, and oil quenched. It was subsequently drawn for two hours at the temperatures shown to the hardness values indicated. The quenched hardness was Rockwell C 58.

mate contact of the cooling air with each casting. The work is almost always tempered subsequently to coalesce the pearlite, and so to improve machinability, and toughness and to lower the hardness. An example of the typical microstructure produced by Process I is shown in Fig. 38.

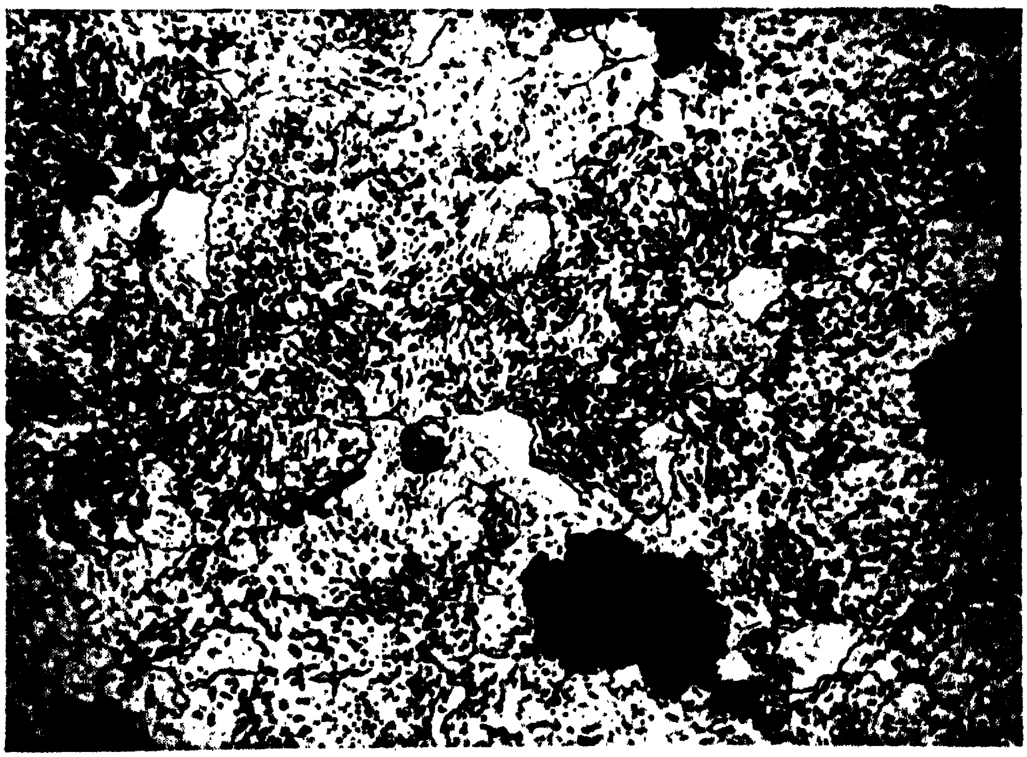


Fig. 38. Representative photomicrograph of a pearlitic malleable iron heat-treated in accordance with the following cycle: After first stage graphitization, castings were cooled to 1650° F., air quenched and tempered to 187 BHN. (Process I). Nital etch, magnification 500 X.

Typical cycle: 15 hours at 1750 degrees F. (FSG)
Cool to 1650 degrees F. and air quench
8 hours at 1260 degrees F. or 1320 degrees F.
(the higher temperature being for the softer iron.)

PROCESS II. (Air-quench, reheat, liquid-quench and temper)

In this method a reheating and liquid quench are interjected between the air-quenched and tempering treatments. This is a very necessary step if the very high-strength high-hardness grades of pearlitic malleable iron are to be produced. It also guarantees uniformity of quench results. The method is well adapted to high-volume plants, since all pearlitic malleable castings may receive their first-stage graphitization and air-quench in one furnace. Those to be liquid quenched are transferred then to the short-cycle reheating furnace, while the others go directly to the tempering or draw furnaces (in accordance with Process I). The reheat furnaces may be short, continuous ones or they may be of the batch type, both of which permit rapid transfer of the hot load to the liquid quenching medium. The tempering cycle for the liquid-quenched work is generally somewhat shorter than that for air-quenched castings. Average properties obtained by one large producer using this method are plotted in Fig. 39. The microstructure of an iron of this type may be seen in Fig. 30.

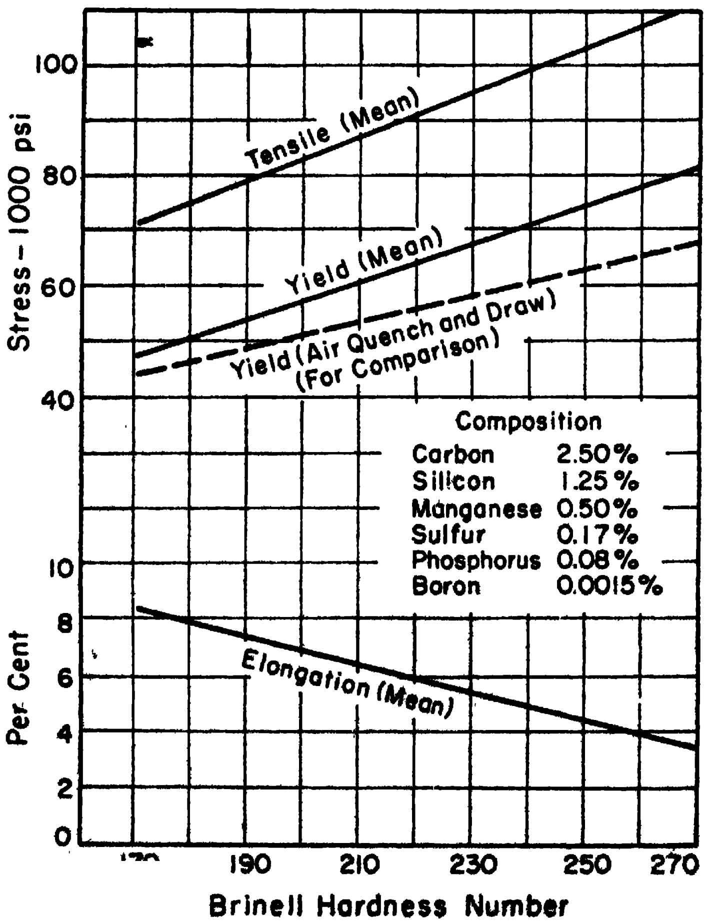


Fig. 39. Properties attained from pearlitic malleable iron which was air cooled after first stage graphitization, reheated, liquid quenched, and drawn. (Process II.)

Typical cycle: 15 hours at 1750 degrees F. (FSG)
Cool to 1650 degrees F. and air quench.
Reheat to 1600 degrees F. and hold for 35 minutes.
Quench in oil (at 130-135 degrees F.)
Temper 3½ hours at 1180 degrees F.

PROCESS III. (Liquid-quench and temper)

Following completion of first-stage graphitization, the temperature is lowered (to prevent cracking), the work is liquid-quenched, and finally tempered. The proportion of pearlitic malleable iron made in this way is not great, since Process II is preferable because of better control over the combined carbon and reduced susceptibility to quench-cracking. Also, with Processes I and II the gates may be ground following the air-quench (when the metal is softer than in the hard-iron state). Any localized hardening developed by grinding at this time is eliminated by the tempering treatment that follows. Such treatment is not possible with Process III.

Typical cycle: 24 hours at 1700 degrees F. (FSG)
Cool and stabilize at 1550 degrees F.
Oil quench
Temper 1½ hours at 1200 degrees F.

PROCESS IV. (Malleablize, reheat, and air-quench)

This method makes it possible to put all production through the regular malleablizing cycles and then reconvert any portion of the ferritic malleable to pearlitic. Only a small continuous reheat furnace is required. The process, however, is not widely used, mainly because of the limited properties possible. A final tempering will render the metal more machinable, as well as improve ductility.

Typical cycle: Full malleablization.
Reheat to 1650 degrees F. and hold 45 minutes.
Air quench.

PROCESS V. (Malleablize, reheat, liquid-quench, and temper)

A considerable tonnage of pearlitic malleable iron is made by this method. As in Process IV, all castings are first fully malleablized and are then heated to above the A_{c_1}. But with Process V the reheating temperature is lower, the quench is in liquid, and the work is always tempered. The quantity of combined carbon may be regulated by adjusting the reheat cycle, the tempering cycle, or both. Low reheat temperatures and long tempering times at relatively high subcritical temperatures favor higher ductility and machinability, but lower strengths. By the selection of a reheating time and temperature such that the austenite does not become saturated with carbon, the danger of developing quench cracks is removed. The untransformed ferrite can absorb enough of the quenching strains to prevent cracking. With the appropriate base iron, any of the grades of pearlitic malleable iron can be manufactured by this method. Nominal strengths obtained by two different producers are shown in Fig. 40 at various levels of hardness.[70]

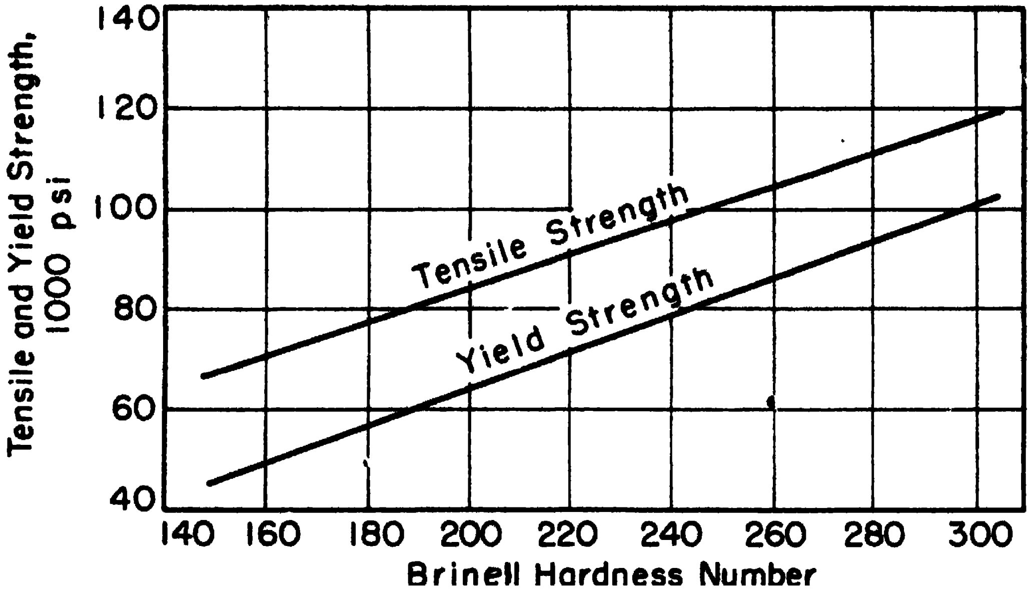


Fig. 40. Typical tensile properties attained for pearlitic malleable irons manufactured by Process V.

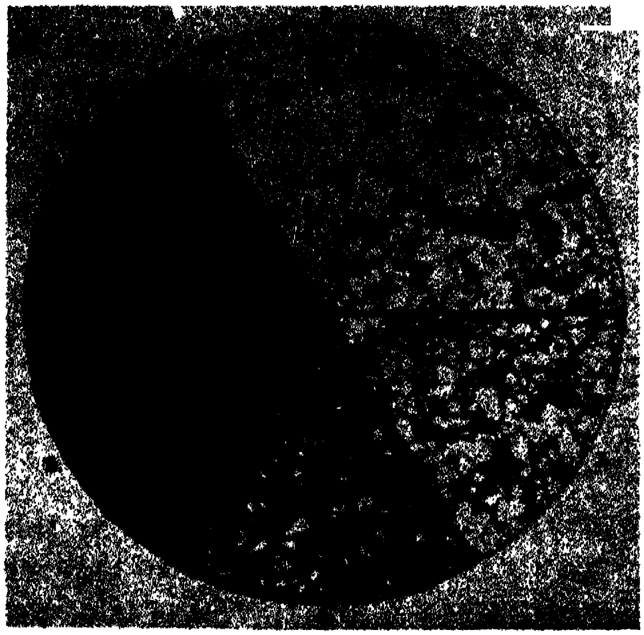


Fig. 41. Photomicrographs showing progressively more combined carbon with progressively higher strength and hardness (Process V). Magnification 100 ×, nital etch. The following table lists properties for the respective microstructures.

Number	BHN	Tensile Strength, psi	Yield Strength, psi	Elongation, per cent
1	120	57,000	38,400	25
2	150	66,300	45,200	20
3	163	71,400	51,000	17
4	179	80,500	58,000	12
5	228	97,500	76,000	7
6	332	133,000	120,000	1

Typical microstructures are shown in Figs. 33 and 41.

Typical cycle: Full malleablization.
Reheat to 1510 degrees F. and hold 75 minutes.
Oil quench
Temper 75 minutes at 1200 degrees F.

ALLOYED PEARLITIC MALLEABLE IRONS

Alloyed pearlitic malleable castings are made from base irons that solidify white and contain one or more chemical elements in quantities not normally found in standard malleable iron, which affect the heat-treatment in such a way that a regular malleablizing anneal will not result in a ferritic matrix. The alloys added generally have little or no effect on first-stage graphitization, but must serve as carbide stabilizers during eutectoid range or sub-eutectoid tempering treatments. They also may exert beneficial side effects, such as increasing the depth of hardening, strengthening the matrix, or stabilizing the structures at high-temperature service. Some of the alloys that may be added are manganese, molybdenum, and sulfur. To complement these, other elements are sometimes also used (a) to counteract the inoculating effect of the prime additive (e.g. Bi, Te), (b) to improve the strength, corrosion resistance, and graphite distribution (e.g. Cu), or (c) to offset any retarding influence of the prime alloy on first-stage graphitization (e.g. B). The carefully weighed additions may be made to the furnace (if the entire heat is to be cast for pearlitic malleable production) or to weighed amounts of white iron in large ladles. Fully martensitic structures in sections as heavy as 2 inches may be developed by air quenching from 1600 degrees F. pearlitic malleable irons that have been suitably alloyed.

PROCESS VI. (Alloy, air-quench, and temper)

Suitable alloying makes it possible to quench a load of castings of as much as ten tons in circulating air and thereby obtain a uniform pearlitic structure throughout the load. This feature has made the electric elevator type of furnace popular for heat-treating pearlitic malleable by this method, although other equipment permitting a fast air quench is equally effective. Probably the commonest alloying element for this process is manganese. By controlling the amount of manganese in excess of that required to balance the sulfur (2 x per cent S plus 0.15 per cent), various grades of pearlitic malleable irons as desired may be produced by a single heat-treating cycle. Thus, the process finds good acceptance among those plants whose total daily tonnage of pearlitic malleable may not be immense, but which have to meet the specifications for several different grades. Besides its effect in improving the quench, manganese sufficiently stabilizes the secondary carbides so that graphitization during tempering is practically completely suppressed, allowing the spheroidizing reaction

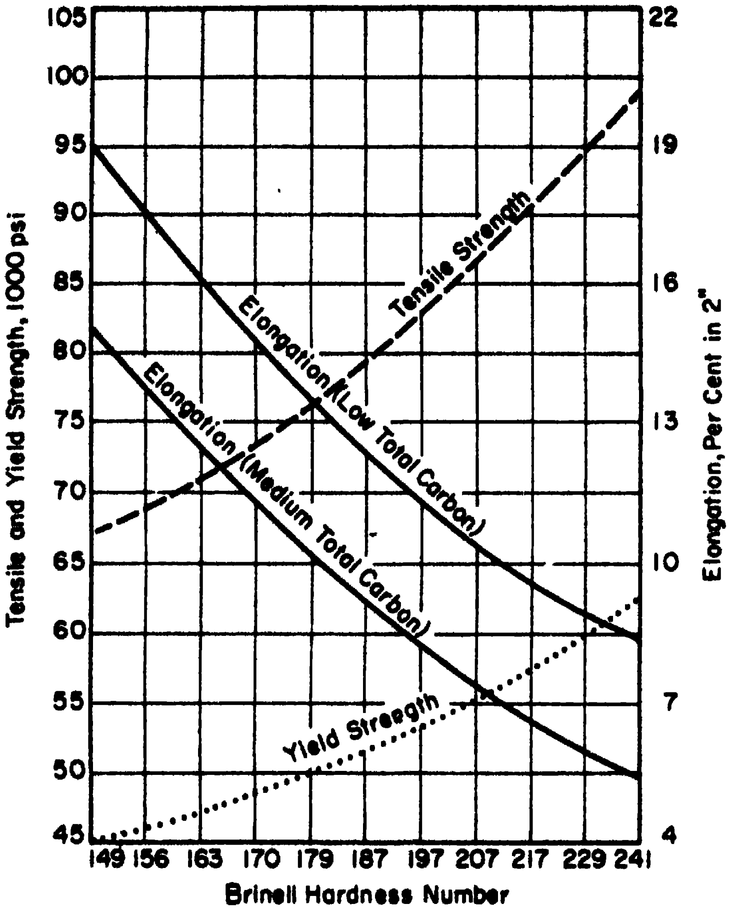


Fig. 42. Typical mechanical properties of air quenched and spheroidized, manganese alloyed, pearlitic malleable iron.

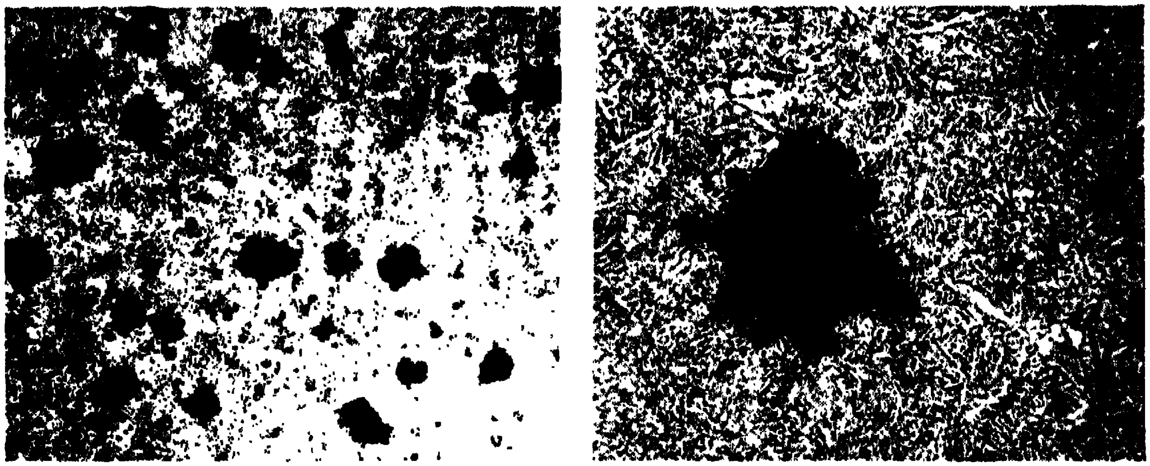


Fig. 43. Representative microstructures of manganese alloyed pearlitic malleable irons, nital etch, magnification 100 X (left) and 500 X (right).

to predominate. Therefore, longer tempering (or spheroidizing) times may be used to advantage so as to insure uniformity of results throughout large castings and large loads of castings. Properties common to this method are presented in Fig. 42.

Typical cycle: 24 hours at 1720 degrees F.
Air quench to 900-1100 degrees F.
Temper 34 hours at 1300 degrees F.

Typical microstructures—See Figs. 31 and 43.

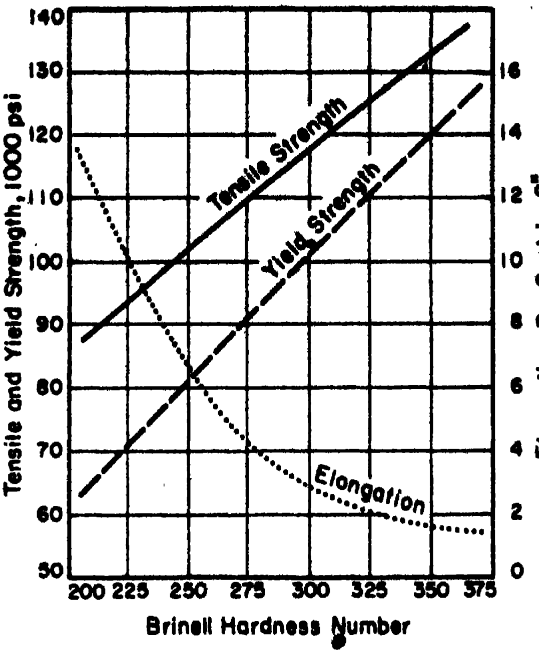


Fig. 44. **Typical mechanical properties of manganese alloyed, oil quenched, and tempered high strength pearlitic malleable iron.**

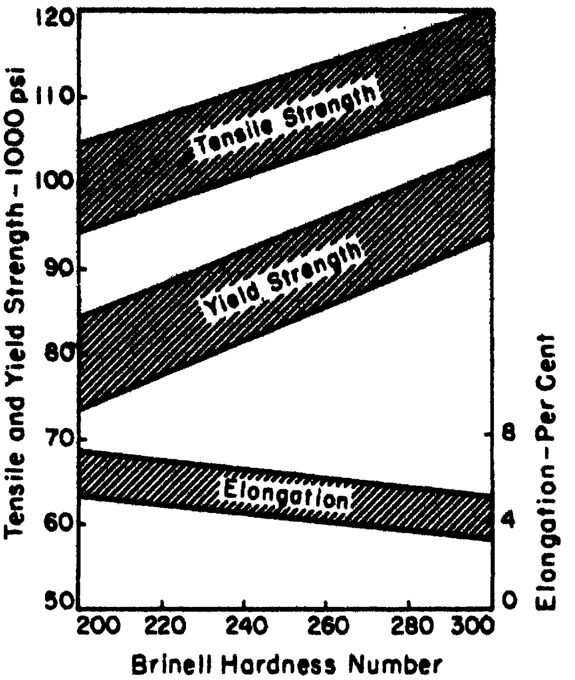


Fig. 45. **Relationship between the Brinell hardness and mechanical properties of oil quenched and drawn, sulphur alloyed pearlitic malleable.**

PROCESS VII. (Alloy, air-quench, reheat, liquid-quench, temper)

This method yields a wide range of possible mechanical properties. Not only is it applicable to the straight manganese- or molybdenum-alloyed pearlitic malleables (cf. Fig. 44), but it also develops the optimum properties in sulfur-alloyed metal, sometimes called malleable-base spheroidal iron,[205] (cf. Fig. 45). When present in some excess over that required to balance the manganese (Mn/S = 3.0 to 3.5), sulfur forms an iron-sulfide complex which apparently favors nucleation of a spheroidal type of graphite during first-stage graphitization. As the Mn/S is lowered, the graphite shape transcends from that of normal temper carbon, through rounded and duplex forms, to that of true spherulites (generally when the Mn/S is less than 1). Since high sulfur retards primary graphitization, heavier sections may be cast white in this alloyed iron. On the other hand, since excess sulfur stabilizes also the massive carbides, a graphitizer (e.g. silicon, boron) is commonly added along with the sulfur to hasten first-stage graphitization. The retarding influence of the sulfur permits longer tempering cycles without any great loss of combined carbon through graphitization, thus equalizing the heat-treating results. A typical microstructure is shown in Fig. 46.

Typical cycle: 35 hours at 1720 degrees F.
Cool to 1550 degrees F.
Air quench
Reheat to 1575 degrees F. and hold 45 minutes.
Oil quench
Temper 15 hours at 1300 degrees F.

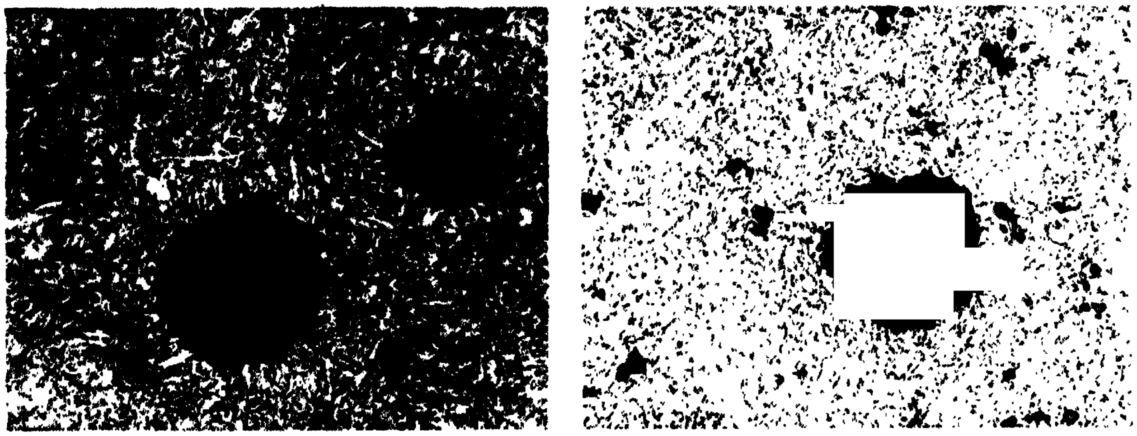


Fig. 46. Typical microstructures of oil-quenched and drawn sulfur-alloyed pearlitic malleable irons. The structure at the left resulted from drawing at 1100° F. for 16 hours and had a 269 BHN. A draw temperature of 1345° F. for 16 hours produced the structure on the right with a 212 BHN. Note the spheroidal form of the cementite. Nital etch, magnification 500 ×.

Process VIII. (Alloy; malleable cycle)

This method is useful for the small plant desiring to make pearlitic malleable iron without capital outlay for special heat-treating equipment and without tying up existing production facilities for handling only a small lot or a few lots of castings. It is also employed to some extent where a continuous car-pot type anneal is available. In such case the relatively uniform control of the cycle promotes uniformity of product. A suitable alloying addition of a carbide stabilizer is made to the base iron in ladles, and the resulting castings are heat-treated right along with the unalloyed white iron in a conventional malleablizing anneal. While the unalloyed work will come out fully ferritized, the alloyed castings will be (lamellar) pearlitic malleable. This method does not offer too

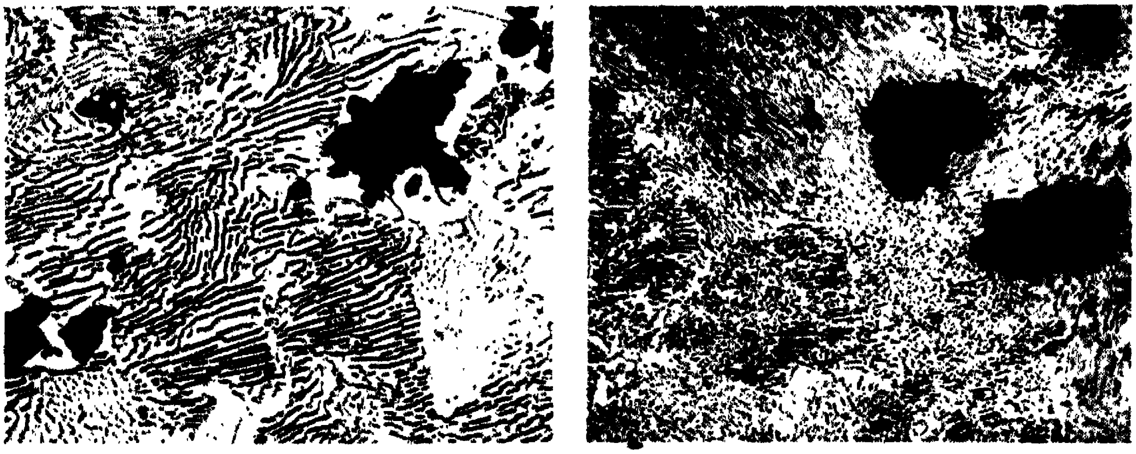


Fig. 47. Microstructure of manganese-alloyed pearlitic malleable iron. The structure on the left is representative of a material processed by the normal malleablizing cycle. The matrix consists of coarse laminar pearlite. The material meets the specification requirements of ASTM Grade 48004

The photomicrograph on the right shows a semi-spheroidized pearlitic matrix resulting from both alloying and a controlled heat-treatment. The material meets requirements for both ASTM Grades 48004 and 53004.

great flexibility for varying properties, but the pearlitic malleable irons made in this way have satisfied the requirements of many service applications, particularly where wear resistance is required.

Typical cycle: Normal malleablizing cycle.

Typical Microstructure: Fig. 47.

In Fig. 48 each of the eight pearlitic malleable production processes is schematically depicted.

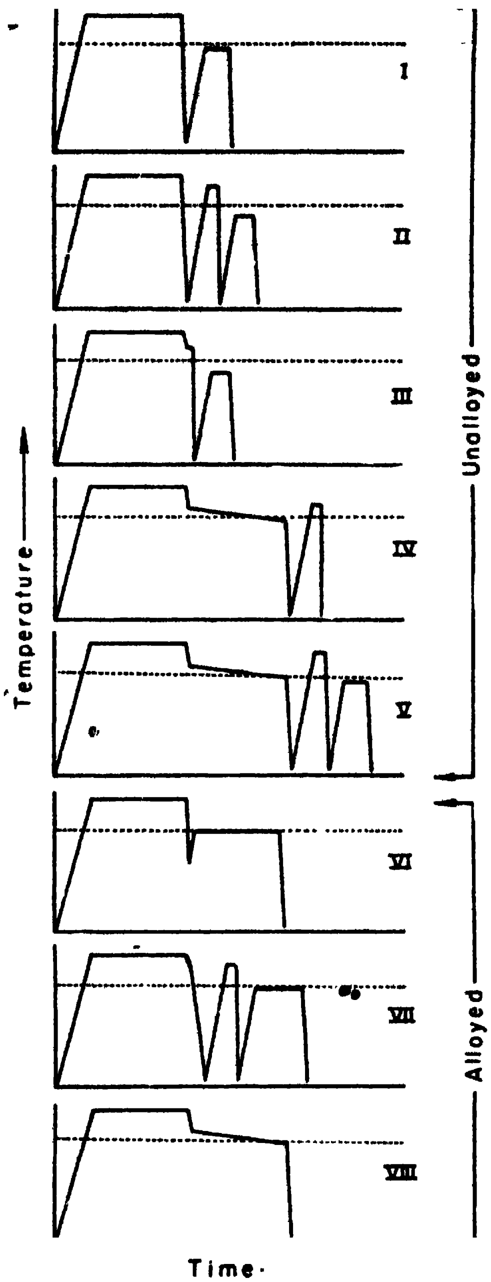


Fig. 48. **Sketches, showing schematically the cycles commercially employed in the production of pearlitic malleable iron.**

HARDENING MALLEABLE IRON

The presence of carbon is a prerequisite for any ferrous material to respond well to hardening. Plain low-carbon steels therefore cannot be hardened by any simple heating and quenching treatment.

On the other hand, the soft carbon-free ferritic matrix of standard malleable iron can be hardened very readily through heating into or above the critical temperature range for a brief period and quenching. This phenomenon is possible because carbon is stored up in the compact graphite nodules that are uniformly distributed throughout the structure. It becomes available as soon as the iron is heated above the lower critical temperature by dissolving in the autenitic matrix that has now formed. In brief, heating malleable iron into the austenitic range undoes what was accomplished during second-stage graphitization.

Then, if the metal is cooled down through the critical range at a slow rate (e.g. 5 degrees per hour), eutectoid graphitization will reoccur, and the normal ferrite and temper carbon structure of standard malleable iron will be restored. However, cooling at a rapid rate through the eutectoid range allows insufficient time for graphitization to proceed to any extent; whatever carbon is in the austenitic solid solution hence will precipitate out as combined carbon. At extremely rapid cooling rates the austenite will transform to martensite, which is extraordinarily hard. At slower rates the austenite will transform to pearlite, which is of intermediate hardness.

This unique characteristic of malleable iron makes it possible to finish the castings to final dimensions, taking full advantage of the excellent machinability of malleable, and then to harden those parts of the castings that are to be subjected to wear or abrasion. The hardening may be carried out in a muffle furnace, by electric induction methods, or by heating in a flame of high-temperature, salt or lead bath. Because of the relatively high thermal conductivity of iron, furnace treatments usually heat the casting throughout and, hence, will result in through hardening. With the other techniques mentioned, it is possible to obtain in a very short time interval a high heat input on the parts exposed, so that localized hardening will result without affecting the properties of malleable elsewhere in the casting.

Regardless of what method of heating has been employed, the work is always quenched in order to obtain maximum benefit from the treatment. The more drastic the quench the harder will be the treated metal. Water quenching is generally preferable for flame hardening; oil quenching is usually satisfactory for induction-treated parts.

Carbon that already exists in the combined form in an iron matrix at room temperature will dissolve in and saturate the austenite formed on heating malleable iron to above the critical temperature range much faster than elemental carbon can pass into solution from the graphite nodules. Therefore, pearlitic malleable irons will respond more rapidly to hardening treatments than will standard malleable iron, which has no combined carbon in the matrix.

While any type of pearlitic malleable iron which contains at least 0.35 per cent carbon in the combined form can be hardened satisfactorily by the proper selection and regulation of one of the recommended hardening procedures, a matrix consisting of fine, dense, and well dispersed spheroidite has been found to give the fastest response. Induction heating methods permit easy control of the process and give better and more consistent results. For example,[89,189] a case depth of 0.060-inch with a hardness of at least 50 Rockwell-C is obtainable by means of a 9600-cycle machine operating between 32 and 75 KW, or a 3000-cycle unit running between 25 and 100 KW, or a 300,000-347,000-cycle unit operating between 35 and 92 KVA, using a single-turn coil. A time interval of a few seconds is adequate in induction hardening. Higher case hardness, deeper cases, and a more homogeneous hardened surface will result from longer heating periods or greater power input. As Fig. 18 illustrates, certain compositions favor higher hardenability.[92]

Ferritic malleable irons that are water-quenched from temperatures just below the eutectoid range will be somewhat (e.g. 15-20 BHN) harder than similar irons that have been slowly cooled from that temperature.[215,253] Presumably this phenomenon results from supersaturation of the ferrite with carbon, nitrogen, or both. Subsequent aging at temperatures above 125 degrees F. will cause gradual softening. Inasmuch as the actual change in hardness is so relatively small, no commercial applications of quench-aging malleable iron are known.

A number of specific examples of case-hardened malleable and pearlitic malleable irons appear elsewhere in this book in the chapters on uses of malleable castings and on pearlitic malleable irons.

GLOSSARY

Acicular—A structure characterized by needle-shaped constituents.

Aerate—To fluff-up molding sand to reduce its density.

Air Furnace—A furnace of the reverberatory type in which the metal is melted, superheated and refined in batch operations, or superheated and refined in duplexing, by a flame from burning fuel, introduced at one end, which passes over the charge to the stack at the other end of the hearth.

Air Hammer—Pneumatic tool for removing excess metal from castings.

Allotriomorphic—Exhibiting imperfect geometric crystalline arrangement (normal for grains in metals) due to external circumstances in crystallizing.

Allotropy—The property, shown by certain elements, of being capable of existence in more than one form, due to differences in the arrangements of atoms or molecules. Examples are iron in the alpha and gamma states and gray and white tin.

Alloy—A substance having metallic properties and being composed of two or more chemical elements of which at least one is a metal. It usually possesses properties different from those of the components.

Alloying Element—A chemical element added to one or more other chemical elements, at least one of which is a metal; this addition is generally made to modify the properties of the base metal.

Alpha Iron (**α-iron**)—The body-centered cubic crystal form of iron which is strongly magnetic up to 1414 degrees F. and stable to 1670 degrees F.

Alumina (Aluminum Oxide) (Al_2O_3)—The only oxide of aluminum. It is used in the foundry industry for abrasives, refractories, etc.

Angstrom Unit—A unit of length equivalent to 10^{-10} meters. This unit is used in measuring ultra-short wave lengths, such as those of X-rays, and space lattice parameters.

Anneal—1. A heat treatment involving the heating and cooling for the purpose of softening metals. For steel it consists of heating above the critical temperature followed by slow cooling, generally in the furnace.

2. In the malleable industry, the process of graphitizing white iron consisting of first stage (q.v.) and second stage (q.v.) treatment, sometimes referred to as malleablizing.

Annealing Pot—Metal containers in which parts are packed for an annealing or malleableizing treatment.

Arbor—A metal shape embedded in, and used to support, either green or dry sand cores in the mold.

Austempering—see "Isothermal Heat Treatment."

Austenite—A solid solution in which gamma iron is the solvent, characterized by a face-centered cubic crystal structure.

Austenitizing—Heating to and holding within the temperature range where austenite is stable.

Back Draft—Reverse taper which would prevent removal of a pattern from a mold or a core from a corebox.

Backing Sand—Reconditioned sand used for ramming main part of mold after pattern has been covered with facing sand.

Bainite—A micro-constituent formed by the decomposition of a eutectoid by cooling rates slower than those required for martensite formation and faster than those required for pearlite or the stable constituent. In steel and iron, it is formed by the decomposition of austenite at cooling rates or temperatures between those of the formation of pearlite and martensite. Bainite takes different forms, varying from a feathery form in the upper transformation range to an acicular form in the lower range.

Bake—To harden and strengthen a bonded and molded sand form by heat-curing the contained bond.

Band, Mold—A steel frame placed inside a removable flask to reinforce the sand at the parting line, thus eliminating the need for a jacket during pouring.

Bar, Flask—A rib in the cope of a tight flask to help support the sand.

Bar, Rapping—A short heavy bar used to rap a pattern as it is drawn.

Bay—Longitudinal division of a foundry floor.

Bed, Coke—First layer of coke placed in a cupola.

Bentonite—A colloidal clay (montmorillonite) derived from volcanic ash and used as a binder in compounded sands for the foundry for increasing both green and hot strength. It is found primarily in the Dakotas, Wyoming and Mississippi.

Bentonite mined in Dakota and Wyoming is called Western, that mined in Mississippi is called Southern.

Blackheart Malleable Iron—see "Malleable Iron."

Blast Cleaning—A process for cleaning or finishing metal objects by use of an air blast or centrifugal wheel that throws abrasive particles against the surface of the parts to be cleaned. Small, irregularly shaped particles of steel or iron are used as the abrasive in grit blasting, sand in sandblasting, and steel balls in shot blasting.

Blast Furnace—In ferrous metallurgy a shaft furnace supplied with an air blast, usually hot, and used for the production of pig iron by melting iron ore in a continuous operation. The raw materials (iron ore, coke and limestone) are charged at the top, and the molten pig iron and slag, which collect at the bottom, are tapped out at intervals.

Blind Riser—An internal riser which does not reach to the exterior of the mold.

Blow—A term describing the trapping of gas in castings, causing voids in the metal.

Boron—A non-metallic element of atomic number 5.

Bosh—The section of a cupola where the diameter increases to a maximum above the tuyeres.

Boss—A relatively heavy, but short, projection on a casting.

Bot—A mass of clay used to stop the flow of metal from the taphole of the air furnace or cupola.

Bottom Board—1. Bench and squeeze molding—a wood, asbestos board, or metal plate of size slightly less than the inside flask dimensions that is used for squeezing the drag in mold making. Subsequently, it supports the mold when set out on the floor or on a conveyor.

2. Floor molding—a wood or metal plate held so as to support both the mold and flask.

Box Mold—See Jacket, Mold.

Brazing—Joining metals by fusion of non-ferrous alloys that have melting points above 800° F., but lower than those of the metals being joined.

Breast—The lining of a melting furnace in the vicinity of the tap hole.

Bridge—Cross wall in a furnace. In an air furnace, the front bridge is the end wall through which the fuel is injected. The rear bridge is the low wall separating the hearth from the stack.

Bridging—Local freezing across a mold before the metal below solidifies. Solidification of slag within the cupola at or just above tuyeres, or "hanging up" of a large charge piece.

Brinell Hardness Number—A number derived from a standard hardness test (Brinell test) which indicates the hardness of the material.

British Thermal Unit (BTU)—A unit of heat. The quantity of heat required to raise the temperature of 1 pound of water 1° F. at or near its point of maximum density.

Bung—One of the several arches that form the roof of an air furnace. It is made up of high-temperature bricks joined together in a long, arched metal frame (the bung frame).

Calorie—A cgs unit of heat. The quantity of heat necessary to change the temperature of one gram of water from 3.5 to 4.5 degrees Centigrade.

Captive Foundry—A foundry that is an integral part of a manufacturing establishment, where foundry operations are a part of the regular plant operation.

Carbide—A compound of carbon with one or more metallic elements.

Carbon—A non-metallic element of atomic number 6. It occurs in nature in three forms: amorphous, graphite and diamond and is an important alloying element in ferrous metallurgy. As graphite, it promotes machinability; as a carbide, it improves strength and wear resistance. In molten ferrous metals, it promotes fluidity.

Carbon Equivalent—A relationship between carbon, silicon and phosphorus in cast irons: $\text{C.E.} = \%\ \text{T.C.} + \frac{\%\ \text{Si} + \%\ \text{P}}{3}$

Carbon Steel—Steel which owes its properties chiefly to the presence of carbon without substantial amounts of other alloying elements.

Carbonyl Iron—A very high purity iron obtained by the thermal decomposition of iron carbonyl [$Fe(CO_4)$].

Carborundum—Silicon carbide (SiC).

Carburizing—Adding carbon to the surface of iron base alloys by heating the metal above A_3 and below its melting point, while in contact with carbonaceous solids, liquids or gases.

Case Hardening—A process of hardening a ferrous alloy so that the surface layer or case is made substantially harder than the interior or core.

Casting (noun)—A metal object obtained by allowing molten metal to solidify in a mold, the shape of the object being determined by the shape of the mold cavity.

Casting (verb)—The act of pouring molten metal into a mold.

Casting Yield—The weight of casting or castings divided by the total weight of metal poured into the mold, expressed as a per cent.

Cast Iron—1. In general, a family of ferrous alloys characterized by high carbon and appreciable silicon. Carbon contents range from 2 to 4½% and silicon up to 3%.

2. Specifically, gray cast iron in which at least a part of the carbon precipitates as graphite while the metal is still in the mold. This distinguishes cast iron from malleable iron in which the graphite is precipitated by heat treatment.

Cast Plate—See Match plate.

Cementite—A hard, brittle, intermetallic compound essentially composed of iron and carbon, known as iron carbide, having the approximate chemical formula Fe_3C. It is observed in the microstructure of irons and steels.

Centigrade—1/100 of the difference between the temperature of melting ice and that of boiling water under standard atmospheric pressure; °C = 0.555 (°F − 32).

Centrifugal Casting—A process of making castings in a rotating or spinning mold.

Chaplet—A metal support or spacer used in molds to maintain cores, or parts of the mold which are not self-supporting, in their proper positions during the casting process.

Charcoal Pig Iron—A pig iron produced in the blast furnace using charcoal as the reducing agent.

Charge—1. The materials placed in a melting furnace.
2. Casting placed in a heat treating furnace.

Check—A minute crack in the surface of a casting, caused by unequal expansion or contraction during cooling.

Cheek—The intermediate part of a flask or mold which has more than two parts.

Chill—A formed piece of metal applied to the exterior or interior surface of a casting to hasten solidification.

Chilling—1. A method of compensating for unevenness of section in a casting by the use of chills.
2. A method of chilling iron in the ladle by adding cold metal.

Chipping—Removing fins and other excess metal from castings with a pneumatic or hand chisel.

Chromium—A metallic element, atomic number 24, widely used as an alloying element in steel, but kept to a mimum in malleable iron.

Clay—Naturally occurring hydrosilicates of aluminum used as a bonding material.

Coining—A process of either cold or hot forming metals by pressing them to shape and size in a die.

Coke—Coal from which the volatiles have been driven off by heating in the absence of air.

Cold Melting—Production of molten white iron in air or electric furnaces in which the charge is solid metal.

Cold Shut—An imperfect junction between two flows of metal in a mold.

Cold Working—Permanently deforming a metal below its recrystallization temperature.

Combined Carbon—The carbon in iron or steel which is combined with other elements, usually iron, and therefore is not in the free state as graphite or as temper carbon.

Compressive Strength (ultimate compressive strength) — The ultimate compressive strength is the maximum stress that a brittle material can withstand without fracture when subjected to compression. This property is not well defined in a ductile material.

Cope—The upper or topmost section of a flask, mold, or pattern.

Copper—A metallic element of atomic number 29.

Core—A preformed sand aggregate placed in a mold to shape the interior contours, such as interior channels of various shapes, or undercuts on the surface of the casting.

Core Box—The pattern for cores, having a cavity that is contoured to the desired shape of the core to be made therein.

Core Drier—A support used to keep cores in shape while being baked.

Core Plate—A flat plate used to support cores while being baked.

Core Print—That part of a mold cavity into which the supporting portion of a core is placed, thus locating and anchoring the core in the mold.

Corundum—Native form of alumina (q.v.).

Crack, Cold—A crack which occurs in a casting at or near room temperature.

Crack, Hot—A crack in a casting which occurs at some elevated temperature, generally above 600° F. (Compare with hot tear.)

Cracking Strip—A fin added to a casting to prevent hot tears or hot cracks.

Creep—The flow or plastic deformation of metals held for long periods of time at stresses lower than the normal yield strength. The effect is particularly important if the temperature of stressing is in the vicinity of the recrystallization temperature of the metal.

Critical Temperature—That temperature or range of temperatures at which a phase transformation or abrupt change in property occurs during the heating or cooling of an alloy. In malleable terminology it commonly refers to the eutectoid transformation temperature. See "Transformation Temperature."

Crucible—A pot or receptacle made of refractory materials such as high temperature resisting alloys, graphie, alundum, magnesia, or silicon carbide, bonded with clay or carbon, and used in melting or fusion of metals.

Crush—A casting defect caused by sand displacement, at or near the parting line, on closing the mold.

Crystal—A physically homogeneous solid in which the atoms, ions, or molecules are arranged in a tri-dimensional, repetitive pattern.

Cupola—A vertical, cylindrical, or shaft furnace, usually lined with refractories, used for melting metal in direct contact with coke as fuel by forcing air, introduced under pressure through openings (called tuyeres) near its base, upwards through the charge.

Curie Temperature—The temperature at which a material, on heating, ceases to be ferromagnetic.

Cut—(a) To recondition molding sand by mixing on the floor with a shovel or blade-type machine.
(b) To form the sprue cavity in a mold.
(c) To erode away part of a mold or core by the metal stream.
(d) To dilute.

Damping Capacity—Ability of a metal to absorb vibration, changing the mechanical energy into heat. Damping capacity is the term applied when the vibration is caused by stresses of engineering magnitude (up to the yield strength of the metal). Measurements made under extremely low stresses lead to the result called internal friction.

Decarburization—Loss of carbon from the furnace of a ferrous alloy as a result of heating in an oxidizing atmosphere which reacts with the carbon.

Decibel—Unit for measuring the ratio of two amounts of acoustical power.

Deformation—Change in dimensions, as the result of an applied stress.

Delta Iron (δ iron)—The body-centered cubic crystal form of iron, which is stable from 2550 degrees F. to the melting point.

Dendrite—A tree-like crystal formed during solidification of metals or alloys. Dendrites usually grow inward from the mold surface, extending branches from a central trunk in a manner resembling a fir tree. (Dendron is the Greek word for tree.)

Deoxidize—To remove dissolved oxygen from molten metal.

Dielectric Core Baking—Heating cores to baking temperatures by means of high-frequency equipment. This process is particularly well adapted to thermo-setting resin core binders.

Diffusion—The process by which atoms migrate as a result of their random thermal motion, usually in the direction from regions of high concentration towards regions of low concentration, in order to achieve homogeneity of the solution, which may be either a liquid, a solid, or a gas.

Dilatometer—An instrument for measuring expansion or contraction caused in a metal or sand sample by changes in temperature or structure.

Directional Solidification—Solidification of a cast member in the direction of increasing temperature gradients.

Draft, Pattern—The taper in vertical elements in a pattern, which allows it to be easily withdrawn from a sand mold.

Drag—The lower or bottom section of a flask, mold, or pattern.

Draw—(a) Surface shrink on a casting or riser.
(b) To remove a pattern from a mold or a core from the core box.
(c) A misnomer for tempering in heat-treating.

Draw Bar—A bar used for lifting the pattern from the sand of the mold.

Drawing (Pattern)—Removing pattern from mold or mold from pattern in production work. See also Tempering.

Drawing (Tempering)—See tempering.

Drop—A mold or casting defect caused by a portion of the cope or other overhanging section falling away from the mold proper.

Dross—Metal oxides in, or on the surface of, molten metal, or trapped in the casting.

Dry Strength (or Dry Bond Strength)—The maximum strength of a molded sand specimen that has been thoroughly dried at 220-230° F. and cooled to room temperature.

Ductility—The ability of a solid to deform plastically under stress.

Duplexing—Melting in one furnace and superheating and refining in another.

Elastic Limit—Greatest stress which a material is capable of developing, without permanent deformation remaining upon complete release of the stress.

Electrode—In electro-metallurgy, a conductor belonging to the class of metallic conductors, but not necessarily a metal, through which electric current enters and leaves arc furnaces or electrolytic baths. In welding or arc applications, the two conductors between which the arc forms.

Electrolytic Iron—A very high purity (99.95%) iron, produced by electrolysis of an iron-containing bath.

Elongation—In a tension test, elongation is the total amount of permanent extension of the gage length, measured after the specimen has fractured, and is expressed as a percentage increase of the original gage length.

Endurance Limit (see fatigue limit).

Endurance Ratio (see fatigue ratio).

Eutectic—An alloy having the lowest melting point possible with the given components.

Eutectoid—An alloy of the lowest transformation temperature possible with the given components.

Extensometer—An instrument for measuring deformation in a material while it is under stress.

Facing Sand—Specially prepared molding sand, which is used in the mold adjacent to the pattern to produce a smooth casting surface.

Fahrenheit—1/180 of the difference between the temperature of melting ice and that of boiling water under standard atmospheric pressure; $°F = 1.8° C + 32$.

Fatigue—Tendency of a metal to break, under conditions of repeated cyclic stressing, at levels considerably below the tensile strength.

Fatigue Limit—The limiting value of the stress below which a material can presumably endure an infinite number of cycles of stress, that is, the stress at which the S-N diagram becomes horizontal and appears to remain so.

Fatigue Ratio—The ratio of fatigue limit or fatigue strength at N cycles to the static tensile strength.

Fatigue Strength—The maximum stress which a material can sustain, for a given number of stress cycles, without fracture.

Feeder (see Riser).

Feed Metal—The liquid metal that passes from the riser to the casting to make up for the volume decrease on cooling and solidification of the metal, thus eliminating shrinkage from the casting.

Ferrite—a. A solid solution in alpha iron characterized by a body-centered cubic structure.

b. A compound of sintered oxides used in magnets and characterized by electrical resistivity.

Ferro-alloys—Commercial iron alloys used to alloy iron or to deoxidize; specifically, ferro-boron, ferro-chromium, ferro-manganese, ferro-silicon, ferro-titanium, etc.

Ferrous—Pertaining to iron (ferrum is the latin word for iron).

Fillet—a. In casting, the concave surface joining two other surfaces which make an angle with each other.

b. In pattern-making, the material used on a pattern, or that portion of a pattern or core box, rounding out the internal corners formed by the intersection of two surfaces; may be made of wax, plastic, leather, or wood.

Fin—Thin projection of excess metal on a casting resulting from imperfect mold or core joints.

Fines—A term referring to those sand grains that are substantially finer than the predominating sand mixture. Also, material remaining on 200 and 270-mesh screens and pan when testing for grain fineness and distribution.

First Stage Graphitization (FSG)—The first phase of the annealing cycle in which all massive carbides are decomposed and equilibrium is established between austenite and carbon for the particular holding temperature.

Flame Hardening—Term applied to the surface or localized hardening of ferrous metals containing carbon, by heating with an open flame to a temperature above the critical, and subsequent quenching.

Flask—Metal or wooden frame, without top and without fixed bottom, used in the foundry to hold the sand with which the mold is formed. (A snap flask is a hinged flask that can be removed after completion of the mold; a tight flask remains on the mold during pouring. Lugs are normally provided for clamping cope and drag tightly together. A slip flask is tapered and depends on a movable strip of metal to hold the sand in position. After closing the mold the strip is withdrawn, and the flask can be removed.)

Flask (tight)—A type of molding flask which remains on the mold during pouring.

Flask Pins—Guides to assure proper alignment of the cope and drag of the mold after the pattern is withdrawn.

Flowability—The property of a molding or core sand mixture that permits it to fill all recesses in a pattern.

Fluidity—(a) The ability of a liquid metal to flow readily, as measured by the length of a standard fluidity spiral.

(b) Reciprocal of viscosity.

Fluorspar—Commercial grade of calcium fluoride.

Flux—A material used in melting to provide a protective covering for the molten metal. Also aids in the removal of such undesirable substances as sand, slag, ash or dirt from the molten mixture.

Follow Board—Board which is contoured to fit the pattern and defines the parting surface of the drag.

Forehearth—A refractory-lined container, located near the taphole of a melting furnace, used to store, mix or treat the molten metal.

Founding—The art of melting and casting metals into useful objects.

Foundry—A building or establishment where founding is carried on.

Gagger—Irregular piece of metal used to support sand in deep pockets of molds.

Galling—The damaging of a metallic surface by removal of particles from localized areas during sliding friction.

Galvanizing—The process of coating metal parts with molten zinc by using a dipping process at a temperature of 850-900° F., or by spraying.

Galvanizing Embrittlement—Brittleness caused by cooling irons of certain compositions quickly from a temperature of 400 to 1100 degrees Fahrenheit.

Gamma Iron (γ iron)—The non-magnetic face-centered cubic crystal structure of iron, which is stable between the temperature range of 1690 and 2550 degrees F.

Gangway—Passageway in a foundry.

Gate—1. The connection between the runner and the casting.

2. The assembly of castings, risers, runners fed from a single sprue.
3. Gate (verb)—To design the channels and risers necessary to run and feed castings.

Gated Pattern—One or more patterns, but not on a board or match plate, with gates or runners attached.

Gilsonite—A natural asphalt found primarily in Utah and Colorado. It is similar to pitch and finds application in foundry sand mixtures as a carbonaceous additive to improve surface finish.

Grain—An individual crystal in a metal or alloy; also, an individual or component aggregate when referring to core or molding sands.

Graphitizer—Any substance which increases the tendency of iron carbide to break down into iron and graphite.

Graphitization—The decomposition of carbide to give free carbon as graphite or as temper carbon.

Gray Iron—Cast iron having most or all of its carbon in the form of flake graphite.

Green Sand—A prepared molding sand containing a predetermined amount of moisture for use in the damp or wet condition.

Green Strength—Strength of a tempered sand mixture at room temperature.

Growth—Permanent increase in dimensions of a metal resulting from cyclic or prolonged exposure to elevated temperature.

Hardness—The property of a substance determined by its ability to resist abrasion or indentation by another substance. For metals, hardness is usually defined in terms of the size of an impression made by a standard indenter (Brinell, Rockwell, Diamond, Pyramid, etc., tests).

Hexagonal—A space structure having four axes which intersect at right angles, three coplanar axes at 120° and one at right angles to them.

Hooke's Law—Within the elastic limit of any body, the ratio of the stress to the strain produced is constant.

Hot Dip Galvanizing (See galvanizing).

Hot Sprueing (q.v.)—Sprueing performed before the risers have completely solidified.

Hot Tear—A crack formed in the cooling casting, generally occurring between the solidification point and a temperature about 150° below the solidification temperature.

Hydrogen—A colorless, gaseous element of atomic number 1.

Hyper-eutectoid—An alloy containing more than the eutectoid composition.

Hypo-eutectoid—An alloy containing less than the eutectoid composition.

Impact Resistance—The resistance of a material to breaking by loading or stressing at high rates.

Impact Strength—The energy absorbed by a body fractured under high stress rates, generally expressed in ft. lbs./cu. in.

Impregnation—The treatment of pressure castings with a sealing medium to insure pressure tightness (Media used include sodium silicate, drying oils, with or without styrenes, plastics or proprietary compounds. The process usually consists of evacuation, impregnation under pressure, and sealing by heat).

Inclusions—Particles of impurities, usually oxides, sulphides, silicates, and such, which are mechanically trapped during solidification or which are formed by subsequent reaction of the solid metal.

Induction Hardening—A process of hardening a ferrous alloy through heating above the Ac_3 temperature by means of a high-frequency field, and subsequent quenching.

Inoculant—A material which, when added to molten metal, modifies the structure through a nucleation effect.

Interface—A surface forming a common boundary of two bodies or spaces.

Inverse Chill—The condition in an iron casting section where the interior is white, while other sections are gray in appearance.

Iron Carbide—(See cementite).

Iron Oxide—A chemical compound of iron and oxygen. Three oxides are known, FeO, Fe_2O_3 (hematite) and Fe_3O_4 (magnetite). The latter two ores of iron can be added to metal baths to produce oxidation; they are also used in core and molding sand mixtures to give desirable properties.

Isothermal Heat Treatment—A method of hardening steel or iron by quenching from the austenitizing temperature into a bath which is maintained at a constant temperature level in the transformation range (450 to 1300°). The part is held for a time sufficient to permit transformation and then is transferred to some higher temperature level for tempering and cooling in air.

Isotropic—Having equal physical and/or mechanical properties in all directions.

Jacket, Mold—A wooden or metal form, which is slipped over a mold made in a snap or slip flask, to support the four sides of the mold during pouring.

Jack Star—An irregular piece of hard metal for use in a tumbling barrel.

Jig—Any device so arranged that it will expedite a hand or machine operation.

Jobbing Foundry—A foundry engaged in the manufacture of numerous types of castings not intended for use in its own product. Usually refers to a foundry making castings for many other companies.

Jolt Machine—Molding machine which rams the sand in a mold by jolting or jarring.

Ladle—A metal receptacle, frequently lined with refractories, and used for transporting and pouring molten metal.

Lamellar—Plate-like.

Ledeburite—Cementite—austenite eutectic structure.

Liquidus—A line on a binary phase diagram or a surface on a ternary phase diagram, representing the temperatures at which freezing begins during cooling, or melting ends during heating, under equilibrium conditions.

Loose Piece—Part of a pattern or core box so attached that it remains in the mold or core and is then removed after the pattern or core box is drawn.

Lute—To seal with clay or other plastic material.

Machinability—That property of the metal which governs the ease with which metal may be removed by chip formation.

Macrostructure—The structure of metals as revealed by the eye or at a magnification of less than 10 diameters.

Magnesia (Magnesium oxide, MgO)—An oxide of magnesium used as an abrasive in fine polishing and for manufacture of basic refractories.

Magnetic Particle Testing—A nondestructive testing method of inspecting areas on and near the surface of ferrous materials for defects such as hairline cracks, etc.

Malleable Iron—A ferrous alloy produced by the heat treatment of white iron.

1. Blackheart malleable (American type) has a structure of temper carbon imbedded in ferrite.
2. Whiteheart malleable (European type) has a structure of essentially pearlite and temper carbon, although this varies with section, produced by oxidation of white iron during heat treatment.
3. Pearlitic malleable has a structure of temper carbon imbedded in some decomposition product of austenite.

Manganese—A metallic element, atomic number 25. It is used in the iron and steel industries as a mild deoxidizer and is an essential alloying element.

Martensite—A very hard microconstituent found in iron and steel. It has acicular or needle-like appearance and a tetragonal structure. It is produced through severe quenching or by alloying.

Master Pattern—A pattern that is used for making castings that are to become production patterns.

Matchplate—A plate of metal or other materials on which patterns and gating systems split along the parting line and are mounted back to back to form an integral piece.

Matrix—The principal or background phase in a microstructure, in which another constituent, for instance, temper carbon, is embedded.

Mechanical Properties—The properties of a metal determining its behavior under stress.

Melting Zone—The portion of the cupola above the tuyeres in which the charge melts.

Metallography—Study, by means of a microscope, of metal and alloy structures.

Metallurgy—Science and art of extracting metals from their ores, refining them and preparing them for final use.

Metastable Phase—A peculiar state of pseudo-equilibrium, in which the system has acquired energy beyond that needed for its most stable state yet has not been rendered unstable.

Micro-shrinkage—Fine porosity or tiny cavities, of the order of a fraction of a millimeter in size, with irregular outlines.

Microstructure—The structure of polished and usually etched metal and alloy specimens, as revealed by the microscope at magnifications in excess of ten diameters.

Misrun—Casting not fully formed, resulting from metal poured so cold that it solidified before filling the mold completely.

Modulus of Elasticity—In tension, at stresses below the proportional limit, (q.v.) it is the ratio of stress to the corresponding strain, also called Young's modulus.

Modulus of Rigidity—In a torsion test, the ratio of the unit shear stress to the displacement caused by it per unit length in the elastic range. This corresponds to the modulus of elasticity in the tension test.

Modulus of Rupture—The ultimate strength or the breaking load per unit area of a specimen tested in torsion or in bending. This corresponds to the tensile strength in tension.

Mold—The form, made of sand, metal, or refractory material, which contains the cavity into which molten metal is poured to produce a casting of desired configuration.

Mold Weights—Weights placed on top of molds while pouring, to offset internal pressure.

Molybdenum—A metallic element having the atomic number 42.

Mottled Iron—A white iron containing some primary graphite which precipitated during solidification.

Mulling—The process of mixing molding and core sand ingredients under the action of rubbing and stirring.

Nickel—A metallic element of atomic number 28.

Nitriding—A process of shallow case hardening in which a ferrous alloy, usually of a special composition, is heated in an atmosphere of ammonia, or in contact with nitrogenous material, to produce surface hardening by formation of nitrides, without quenching.

Nitrogen—A colorless, odorless, and generally inert gas of atomic number 7. Nitrogen may be used as a protective atmosphere in annealing furnaces.

Nodular Iron—A member of the gray iron family, which has been treated with a special metallic material while in the liquid state to obtain graphite in the spherulitic or nodular rather than flake form on solidification.

Normalizing—A heat treatment, applied to steels and irons, which involves the heating above the lower transformation temperature, holding at temperature for a specified time, and cooling in still air.

Notch Sensitivity—The property of the metal which produces a reduction in impact endurance or static strength of that metal in the presence of stress concentrations caused by scratches, notches, etc. Notch sensitivity is usually expressed as a ratio of the notched to the corresponding unnotched strength.

Nucleation—The formation of nuclei (plural of the Latin word nucleus, literally "kernel"),—see nucleus.

Nucleus—The first structurally determinate particle of a new phase or structure that is in the process of forming. The term is especially applicable to solidification of liquids, recrystallization and other transformations in the solid state.

Oxidation—Any process which increases the proportion of oxygen or acid-forming element or radical in a compound.

Oxygen—A gaseous element of atomic number 8.

Packing or Packing Material—Sand, gravel, mill scale, or similar materials used to support castings packed in annealing pots, to prevent possible warpage under high temperature.

Padding—The application of tapered layers of metal to uniform sections, to permit controlled directional soldification of the part.

Parting Compound—A material dusted or sprayed on patterns or mold halves to prevent adherence of sand and to promote easy separation of cope and drag parting surfaces when cope is lifted from drag.

Parting Line—The plane along which a pattern is divided for molding, or along which the sections of a mold separate.

Pattern—A form around which molding material is placed to shape a mold for casting metals.

Pearlite—The eutectoid of ferrite and iron carbide (cementite), characterized generally by lamellar structure.

Peel—Clean separation of molding sand from casting during shakeout.

Peen—(a) To ram or pack molding or core sand into critical sections of a mold or core.

(b) To cold-work the surface of a metal by repeated impact blows.

Perlite—A highly siliceous volcanic rock that can be expanded by heating into a porous mass. Used as an insulation in foundry sand mixtures.

Permeability—1. Molding sands—permeability is the property of the sand which permits the passage of gases.

2. Magnetic problems—permeability is the ratio of the magnetic induction of the substance to the magnetizing field to which it is subjected.

Phase—A constituent which is completely homogeneous both physically and chemically, which is separated from the rest of the alloy by definite boundaries.

Phosphorus—A non-metallic element, atomic number 15. It is generally regarded as undesirable in ferrous metallurgy.

Pickle—To clean metal surfaces by chemical or electro-chemical means.

Pig Iron—Blast furnace iron that is cast in chilled (pig) molds.

Pipe—A cavity formed by contraction in metal during solidification.

Plastic Deformation—Permanent distortion of a material under the action of applied stresses.

Potentiometer—1. An instrument used with a galvanometer to measure accurately a wide range of electromotive forces.

2. With proper galvanometer scales, an instrument which indicates temperatures by accurately measuring small electromotive forces developed by a thermocouple.

Precipitation Hardening—A process for strengthening or hardening an alloy by the precipitation of a constituent from supersaturated solid solution.

Primary Crystals—The first dendritic crystals that form in an alloy during cooling below the liquidus temperature.

Primary Graphite—Free graphite in the flake, rosette or eutectic form, not precipitated during heat treatment.

Proportional Limit—The greatest stress that a material is capable of sustaining without a deviation from the law of proportionality of stress to strain.

Pyrometer—Instrument for indicating and/or recording temperature.

Quenching—A process of rapid cooling from an elevated temperature, in contact with liquid, gases or solids.

Ram—To pack sand in a mold.

Refractory—1. Noun—heat resistant materials, usually non-metallic, used for furnace and ladle linings, etc.

2. Adjective—the quality of resisting heat.

Rib—a. A bar in the cope of a tight flask to support the sand.

b. A strengthening member of a casting.

Rig—To prepare a pattern and flask equipment for molding.

Riser—A reservoir connected to the casting, which provides liquid metal to the casting during solidification to compensate for the internal shrinkage of the casting as it cools and solidifies.

Rockwell Hardness—A number, determined by the standard Rockwell hardness test, which denotes the hardness of the material. There are various Rockwell scales in use.

Rod—A heavy wire or bar in a sand core used for reinforcing.

Runner—The channel of a gating system through which molten metal flows from the sprue to the castings and risers.

Sag—A decrease in casting thickness caused by sagging of the core.

Sand Cutting—Preparing sand for molding, either by hand or by a machine, the operation also aerating the sand.

Sand Tempering—Adding sufficient moisture to molding sand to make it workable.

Scab—A defect on the surface of a casting which appears as a rough, slightly raised surface blemish crusted over by a thin porous layer of metal.

Scaling—Surface oxidation caused on metals by heating in air or in other oxidizing environments.

Scrap—a. Defective casting.

b. Metal to be remelted.

Sea Coal—Finely pulverized coal that is mixed into molding sands to improve the surface of castings.

Second Stage Graphitization (SSG)—The second phase of the annealing cycle of malleable iron in which the last quantities of carbon, remaining after first stage graphitization, are precipitated as graphite on the nodules formed during first-stage graphitization (q.v.).

Selective Hardening—Obtaining desired degrees of hardness in different areas of a casting.

Shakeout—The operation of removing castings from the mold.

Shear Strength—Maximum shear stress that a material is capable of withstanding without failure.

Shift—A casting defect resulting from a mismatch of cope and drag or the improper placement of a core.

Shrink—In an insufficiently fed casting, the hole or holes left by the shrinkage.

Shrinkage—The decrease in volume accompanying cooling and solidification of metal.

Shrinkage, Patternmaker's—A scale, divided in excess of standard measurement, to allow for the difference in size between the casting and the corresponding mold cavity. Used by patternmakers to avoid calculations for shrinkage.

Silica (Silicon Dioxide) (SiO_2)—An oxide of silicon. The prime ingredient of acid refractories and sand.

Silicon—A non-metallic element, atomic number 14. It is used in ferrous metallurgy as a deoxidizer and essential alloying element.

Sintering Point—A temperature, below the fusion point, at which grains of material begin to adhere to each other. The grains may be sand, ore, metal or refractory. In foundry use the term is understood as the temperature at which the molding material begins to adhere to the casting.

Skimmer—a. A tool used for pulling slag off molten metal.
b. A core in the gating system for tapping slag.

Slag—A product resulting from the action of a flux on the oxidized non-metallic constituents of molten metals. May also be produced by oxidation of the molten bath, ash from the fuel, erosion of the refractories, and floating of non-metallics in the charge.

Slick—A small hand tool for smoothing or patching molds or cores.

Snag—To remove excess metal from a casting by rough grinding.

Soldering—Joining metals by fusion of alloys that have relatively low melting points, most commonly lead-base or tin-base alloys, which are the soft solders. Hard solders are alloys which have silver, copper or nickel bases, and use of these alloys with melting points higher than 800° F. is generally termed brazing.

Solidus—A line on a binary phase diagram or a surface on a ternary phase diagram, representing the temperatures at which freezing ends during cooling, or melting begins during heating, under equilibrium conditions.

Sonims—Solid non-metallic inclusions (see Inclusions).

Specific Heat—The specific heat of a substance is the ratio of its heat capacity to that of water at 15° C.

Spheroidite—An aggregate of globular carbide and ferrite.

Spherodized Cementite—A microstructure in which iron carbide particles occur as small spheres in a substantially ferritic matrix.

Spiegel, or Spiegeleisen—A manganese-containing product of the blast furnace.

Sprue—1. The vertical portion of the gating system through which the metal enters the mold.

2. A generic term to cover all gates, risers, etc., returned to the melting unit for re-melt.

3. To remove gates, runners and risers from the casting.

Sprue Button—A print attached to the top board of a mold to make an impression in the cope indicating where the sprue should be cut.

Spruing—(See Sprue, 3). (See Hot Spruing.)

Stabilizer—Any substance that increases the tendency of carbon to remain as iron carbide, i.e., retards graphitization.

Stack—Section of cupola or blast furnace above the melting zone. In the air furnace the stack is the vertical part beyond the rear bridge wall through which the flue gases escape.

Stack Molding—A molding method by which a number of identical mold sections are placed one above the other and poured through a common sprue.

Stop-off or Stop-off Core—A core used to simplify the parting line of a pattern; that is, to make it unnecessary to carry the parting line above or below its normal position in order to provide for lugs or cored holes.

Strain—1. Deformation—a measure of the change in shape or size of a body, referred to the original shape or size. Strain is a non-dimensional quantity, but it is sometimes expressed in inches per inch.

2. A casting defect—an out-of-shape casting due to upward movement of the cope during pouring due to high ferrostatic head.

Strainer Core—A perforated core in the gating system for restraining slag and other extraneous material from entering the casting cavity.

Stress—The intensity, at a point in a body, of the internal forces or components of force that act on a given plane through the point. Stress is expressed in force per unit of area, pounds per square inch, kilograms per square millimeter, etc.

Strike (Strickle)—A tool with a straight or curved edge for removing excess sand from a mold or core.

Strip—To draw a pattern from a mold or a core from a core box.

Sulfur—A non-metallic element, atomic number 16. Generally regarded as undesirable in ferrous metallurgy, although added in controlled amounts to free-machining steels.

Supercooling—Lowering by rapid cooling the temperature at which a phase transformation would normally occur in an alloy under equilibrium conditions.

Superheating—Raising the temperature of molten metal above the normal melting temperature for more complete refining, greater fluidity, and other reasons.

Swell—A casting defect consisting of an increase in metal section caused by displacement of the mold wall under ferrostatic pressure.

Swirl Gate—A device in the gating system for trapping slag and dross before it gets to the mold cavity.

Tap Hole—Opening in the furnace through which the molten metal is tapped into the spout.

Tapping—1. The process of removing molten metal from the melting furnace.

2. Opening the tap hole (q.v.).

Tear, Hot—(See hot tear).

Tellurium—A semi-metallic element of atomic number 52, used in small quantities in malleable iron to stabilize carbides during solidification.

Temper Carbon—A free or graphite carbon that precipitates from solution during heat treatment (see annealing). This carbon has the form of equi-axed nodules or compact agglomerates of carbon. The term is applied, generally, only to malleable iron.

Tempering—1. A thermal treatment, consisting of reheating quench-hardened or normalized parts to a temperature below the transformation range, and holding for a sufficient length of time to produce the desired properties. (Also called drawing.)

2. A second meaning refers to molding sand, where "tempering" is synonymous with moistening or adding water to develop desired molding properties.

Template—A guide, gage or pattern for checking dimensions or locations.

Tensile Strength—The maximum tensile stress, which a material is capable of sustaining. Tensile strength is calculated from the maximum load during a tension test, carried to rupture, and the original cross-sectional area of the specimen.

Test Lug—A small projection on a casting that may be fractured to test the ductility of the metal in the piece without destroying the casting itself.

Test Sprue—A round sample cast during heating to evaluate by fracture the progress of refining.

Thermal Expansion—The increase in all dimensions which accompanies an increase in the temperature. The coefficient of linear thermal expansion is the ratio of the change in length per degree C. to the length at zero degree C. The coefficient of volume expansion for solids is approximately three times the linear coefficient.

Thermocouple—An assembly of two dissimilar metals which, when joined, produce an electromotive force proportional to the temperature difference between their hot and cold ends. This device, when connected to a suitable potentiometer (q.v.) furnishes a means of temperature measurement.

Tie Bar—A bar shaped connection added to a casting to prevent distortion caused by uneven contraction between two separated members of the casting.

Top Board—A wood board which is used on the cope half of the mold to permit squeezing the mold.

Torsion—1. Pressing of a body by twisting.
2. Strain created in a material by a twisting action.
3. The stress developed within a material resisting the twisting.

Tote Box—A container used for transporting materials.

Transformation Temperature—The temperature or temperature range over which a change in phase occurs. This term is generally applied only to transformations in the solid. The following symbols are used in ferrous metallurgy: *

Symbol	*Transformation*
Ac_1	Start of ferrite to austenite on heating
Ae_1 (A_1)	Lower boundary of ferrite—austenite equilibrium
Ar_1	End of austenite to ferrite on cooling
Ac_2	Loss of magnetism on heating
Ae_2 (A_2)	Curie temperature
Ar_2	Recovery of magnetism on cooling
Ac_3	End of ferrite to austenite on heating
Ae_3 (A_3) *	Upper boundary ferrite—austenite equilibrium
Ar_3	Start of austenite to ferrite on cooling
Ac_4	Start of austenite to delta iron on heating
Ae_4 (A_4)	Lower boundary of delta field—equilibrium
Ar_4	Finish of delta to austenite on cooling
Ac_{cm}	Start of solution of cementite in austenite on heating
Ae_{cm} (A_{cm}) *	Austenite, austenite—cementite boundary—equilibrium
Ar_{cm}	Start of precipitation of cementite from austenite on cooling
Ms	Start of martensite formation
Mf	End of martensite formation

* A_3 applies to hypo-eutectoid steels, A_{cm} to hyper-eutectoid steels.

Trimming—Removing fins and gates from hard iron castings.

Tumbling Barrel—A rotating barrel in which castings are cleaned, also called rolling barrel and rattler.

Tuyere—An opening in a cupola, blast furnace, or converter for introduction of air for combustion.

Vent—A small channel in cores or molds for letting steam, air or mold gas escape as metal fills the mold.

Welding—A process used to join metals by the application of heat. Fusion welding, which includes gas, arc and resistance welding, requires that the parent metals be melted.

White Iron—Cast iron in which substantially all the carbon is present in the form of iron carbide (Fe_3C). Such a material has a white fracture.

In malleable foundry practice, white or hard iron is the material in which the castings, later to be malleablized, are originally cast.

Yield—See Casting Yield.

Yield Point—The first stress in a material less than the maximum attainable stress at which an increase in strain occurs without an increase in stress. In malleable iron testing it is the stress producing an elongation under load of 0.01″ over the gage length of 2″. (See yield strength.)

Yield Strength—The stress at which a material exhibits a specified limiting deviation from the proportionality of stress to strain. The deviation is expressed in terms of strain.

Zircon—Natural zirconium silicate, two-thirds of which consists of zirconia (zirconium oxide, ZrO_2).

BIBLIOGRAPHY

1. SCHUEZ, E., and STOTZ, R., Malleable Iron (*Der Temperguss*), Berlin, Julius Springer, 1930.
2. BRAUER, O., "Origin of Malleable Iron (Grundzuege der Geschichte des Temperguss)," *Z.f.d. Gesamte Giessereipraxis,* Vol. 58, Nos. 43–44 (Oct. 24, 1937).
3. HALL, H. G., "Malleable Cast Iron," *Foundry Trade Journal,* Vol. 62, No. 1231 (March 21, 1940).
4. *Iron Age.* "The Records of Seth Boyden's Experiments on Malleable Cast Iron," Vol. 62 (1898).
5. SCHWARTZ, H. A., *American Malleable Cast Iron,* Cleveland, Penton Publishing Co., 1922.
6. BOYDEN, W. C., BOYDEN, M. N., and BOYDEN, A. J., *Thomas Boyden and his Descendants,* Boston, T. R. Marvin and Son, 1901.
7. *Dictionary of American Biography,* New York, Charles Scribner's Sons, 1928–1936, Vol. 2.
8. FOXBOROUGH, MASSACHUSETTS, *Vital Records to the Year 1850,* Boston, The New England Historic Genealogical Society, 1911.
9. DAVIS, C. G., "Malleable Cast Iron—Its History in the United States," *Journal of the Franklin Institute,* Vol. 148 (1899).
10. VAN DUYNE, PHILIP R., Meeker Foundry Company, Newark, N.J., private communication, October 28, 1954.
11. SIMONDS, H. R. "Marks Century in Producing Malleable Iron," *Foundry,* Vol. 57, 1929.
12. AMERICAN FOUNDRYMEN'S ASSOCIATION, *Cast Metals Handbook,* Chicago, 1940.
13. BEAN, W. R. "Developments in Melting Malleable Cast Iron." *Transactions,* American Foundrymen's Association, Vol. 45 (1937), p. 334.
14. MOLDENKE, R. *The Production of Malleable Castings,* Cleveland. Penton Publishing Company, 1910.

15. Malleable Iron Research Institute. *Certified Malleable Iron,* Cleveland, n.d.
16. Ricketts, P. C. "Physical Tests of Malleable Cast Iron," *Van Nostrand's Engineering Magazine,* April, 1885.
17. American Society for Metals. *Metals Handbook,* Cleveland, 1948.
18. Steel Founders' Society of America. *Steel Castings Handbook,* Cleveland, 1950.
19. Schwartz, H. A., and Junge, C. H. "Young's Modulus of Elasticity and Some Related Properties of Graphitic Materials," *Proceedings,* American Society for Testing Materials, Vol. 41, 1941.
20. Oberg, E., and Jones, F. D. *Machinery's Handbook,* New York, The Industrial Press, 1940.
21. LeRoyer, M. *La Malléable,* Paris, Dunod, 1936.
22. American Society for Testing Materials and American Foundrymen's Association. "Symposium on Malleable Iron Castings," *Proceedings,* American Society for Testing Materials, Vol. 31, 1931.
23. Donaldson, J. W. "Thermal Conductivity of Wrought Iron, Steel, Malleable Cast Iron, and Cast Iron," *Journal,* Iron and Steel Institute, Vol. 28, No. 2 (1933).
24. *Handbook of Chemistry and Physics.* Cleveland, Chemical Rubber Publishing Company, 35th edition, 1953–54.
25. Smithells, Colin D. *Metals Reference Book,* New York Interscience Publishers, Inc., 1949.
26. Marks, Lionel S. *Mechanical Engineers Handbook,* New York, McGraw-Hill Book Company, Inc., 5th edition, 1951.
27. Seitz, Frederick. *The Physics of Metals,* New York, McGraw-Hill Book Company, Inc., 1943.
28. Seitz, Frederick. *The Modern Theory of Solids,* New York, McGraw-Hill Book Company, Inc., 1940.
29. Boas, W. *Physics of Metals and Alloys,* New York, John Wiley and Sons, Inc., 1949.
30. Dunn, L. A., and Green, Paul. General Electric Company, private communication, August 10, 1956.
31. Cottrell, A. H. *Theoretical Structural Metallurgy,* London, Edward Arnold, Publishers, Ltd., 1955.
32. Stanley, J. K. *Metallurgy and Magnetism,* Cleveland, American Society for Metals, 1949.
33. Sisco, F. T. *The Alloys of Iron and Carbon,* New York, McGraw-Hill Book Company, Inc., 1937.
34. Partridge, J. H. *Carnegie Scholarship Memoirs,* American Iron and Steel Institute, Vol. 17 (1928).
35. Malleable Founders' Society. *Technical Bulletin,* No. 299 (December 12, 1940).

36. Marin, Joseph. *Engineering Materials: Their Mechanical Properties and Applications,* New York, Prentice-Hall, 1952.
37. Touceda, E. "Remarks on the Strength and Ductility of Malleable Cast Iron after the Skin has been Removed," *Transactions,* American Foundrymen's Association, Vol. 23 (1915).
38. Touceda, E. "Resistance of Malleable Iron to Repeated Impact Stresses and Comparison of Strength of Machined and Unmachined Malleable Castings," *Transactions,* American Foundrymen's Association, Vol. 34 (1926).
39. Touceda, E. "Malleable Iron Castings," *Product Engineering,* Vol. 8, No. 10 (October, 1937).
40. Malleable Founders' Society. *American Malleable Iron—A Handbook,* Cleveland, 1944.
41. Lansing, James H. "Important Attributes of Malleable Iron," *Proceedings,* International Foundry Congress, Brussels, 1951.
42. Lansing, James H. Tolerances and Specifications of Malleable Castings, *Mechanical Engineering,* Vol. 75, No. 8 (August, 1953).
43. Research conducted at Link-Belt Company's Research Laboratory under the direction of Dr. Lauriston C. Marshall, April, 1957.
44. Schwartz, H. A. "Effect of Machining and of Cross-Section on the Tensile Properties of Malleable Cast Iron," *Proceedings,* American Society for Testing Materials, Vol. 20, Part 2 (1920).
45. Trotzky, G. N. "Factors Determining the Mechanical Properties of Russian Malleable Cast Iron," *Metallurg,* No. 12 (1938).
46. Sandoz, G. A., Howells, N. C., Bishop, H. F., and Pellini, W. S. "Notch Ductility of Malleable Irons," *N.R.L. Report 4725,* Washington, Naval Research Laboratory, 1956.
47. Kempka, G. E., and Heine, R. W. "Effects of Some Melting Variables on Properties of Malleable Iron," *Transactions,* American Foundrymen's Society, Vol. 63 (1955), p. 19.
48. Mahin, E. G., and Hamilton, J. W. "Endurance Limit of Blackheart Malleable Iron," *Transactions,* American Foundrymen's Association, Vol. 43 (1935), p. 41.
49. Murray, W. M. "Report of Fatigue Tests for Malleable Founders' Society," typescript, Cambridge, Mass., 1942.
50. Lauenstein, C. F. "Supplementary Report on Fatigue Strength and Notch Sensitivity of Malleable Iron," mimeographed, Indianapolis, Ind., 1942.
51. Egan, T. E. "Cast Ferrous Metals," *Steel,* Vol. 135, No. 20 (November 15, 1954).
52. Malleable Founders' Society. *Technical Bulletin,* No. 492 (July 22, 1950).
53. Research conducted at National Malleable and Steel Castings Company laboratories, January 13, 1950.

54. Research conducted at National Malleable and Steel Castings Company laboratories under the direction of W. K. Bock, March 26, 1957.

55. Research conducted at Grinnell Company laboratories under the direction of W. A. Kennedy, March, 1956.

56. Research conducted at Brown University laboratories under the direction of W. A. Kennedy, November, 1956.

57. FOSTER, P. FIELD. *The Mechanical Testing of Metals and Alloys,* London, Sir Isaac Pitman and Sons, Ltd., 1942.

58. UNITED STATES DEPARTMENT OF COMMERCE, NATIONAL BUREAU OF STANDARDS, *Circular C447,* Washington, Government Printing Office, 1943.

59. SCHUSTER, L. W. "Relation between Mechanical Properties of Ferrous Metals and Liability to Breakdown in Service," *Metallurgia,* Vol. 17 (1923).

60. SOCIETY OF AUTOMOTIVE ENGINEERS. *Report of Iron and Steel Technical Committee,* New York, 1950.

61. Research conducted in Malleable Founders' Society laboratories by Enrique Touceda and James H. Lansing, 1942.

62. LORIG, C. H., ROSENTHAL, P. C., and SIMMONS, O. W. "Final Report on Study of the Properties of Malleable Castings for Use in Tanks, Combat Vehicles, and other Military Applications," *O.S.R.D. Report 1589,* Washington, Office of Scientific Research and Development, 1943.

63. MARSHALL, L. C., and SOMMER, G. F. "Stress-Rupture Properties of Malleable Iron at Elevated Temperatures," *Proceedings,* American Society for Testing Materials, Vol. 58 (1958).

64. WILDERMAN, M. "Theory and Practice of Blackheart Malleable Iron (Einiges aus Theorie und Praxis des Schwartzgasses)," *Die Giesserei,* Vol. 28, No. 11 (May 30, 1941).

65. Research conducted at Link-Belt Company Research Laboratory under the direction of Dr. Lauriston C. Marshall, December, 1957.

66. LORIG, C. H. "Properties of Commercial Pearlitic Malleable Iron," *Bulletin,* American Society for Testing Materials, No. 105 (August, 1940).

67. MANNWEILER, GORDON B. Eastern Malleable Iron Company, private communication, July 6, 1956.

68. KENNEDY, W. A. Grinnell Company, private communication, October 3, 1956.

69. AMERICAN FOUNDRYMEN'S SOCIETY, PEARLITIC MALLEABLE COMMITTEE. "Comparison of Liquid- and Air-Quenched Pearlitic Malleable Irons: Part I—Duplex Irons," *Transactions,* American Foundrymen's Society, Vol. 64 (1956), p. 91.

70. American Foundrymen's Society, Pearlitic Malleable Committee. "Comparison of Properties of Liquid- and Air-Quenched Pearlitic Malleable Irons; Part II—Duplex, Cold-Melt Process and Alloyed Pearlitic Malleable Irons," *Transactions,* American Foundrymen's Society, Vol. 65 (1957), p. 304.

71. Research conducted at University of Illinois laboratories for Wagner Castings Company.

72. Johnson, H. H., and Bock, W. K. "Investigation of the Effect of Processing Variables on Mechanical Properties of Pearlitic Malleable Iron," *Transactions,* American Foundrymen's Society, Vol. 65 (1957), p. 450.

73. Mannweiler, Gordon B. Eastern Malleable Iron Company, private communication, November 29, 1957.

74. Joseph, C. F. Central Foundry Division, General Motors Corporation, private communication.

75. Forbes, D. P., Paulson, P. A., and Minert, G. K. "Effect of Manganese on Second Stage Graphitization," *Transactions,* American Foundrymen's Association, Vol. 48 (1940), p. 574.

76. Albrecht, W. M. Chain Belt Company, private communication, January 11, 1956.

77. Grover, H. J., Gordon, S. A., and Jackson, L. R. *Fatigue of Metals and Structures,* Washington, Government Printing Office, 1954.

78. Valentine, K. B. "Some Metallurgical Aspects of Pontiac V-8 Engine Pearlitic Malleable Iron Crankshaft," *Transactions,* Society of Automotive Engineers, Vol. 66, 1958.

79. Rehder, J. E. "Effect of Phosphorus Content on Graphitization Rate and Mechanical Properties of Blackheart Malleable Iron," *Transactions,* American Foundrymen's Society, Vol. 60 (1952), p. 627.

80. Research conducted at University of Wisconsin laboratories for Wagner Castings Company.

81. Scholz, W. G., Doane, D. V., and Timmons, G. A. "Effects of Molybdenum on Stability and High Temperature Properties of Pearlitic Malleable Iron," *Transactions,* American Foundrymen's Society, Vol. 63 (1955), p. 251.

82. Research conducted at University of Michigan laboratories for Albion Malleable Iron Company.

83. Puzak, P. P., Schuster, M. E., and Pellini, W. S. "Crack-starter Tests of Ship Fracture and Project Steels," *Welding Journal Research Supplement,* October, 1954.

84. Joseph, C. F. "ArmaSteel," *Iron Age,* Vol. 143, No. 21 (May 25, 1939).

85. *Iron Age.* "Pearlitic Malleable Iron," Vol. 143, No. 16 (April 20, 1939).

86. Mannweiler, G. B. "How Users Benefit from Pearlitic Malleable Castings," *Iron Age*, Vol. 175, No. 20 (May 19, 1955).

87. Kruse, J. E. "Pearlitic Malleable Iron—Interrelation of Heat Treatment, Mechanical Properties and Machinability," *Transactions*, American Foundrymen's Society, Vol. 63 (1955), p. 244.

88. Joseph, C. F. "ArmaSteel," *American Foundryman*, Vol. 4, Nos. 2, 3, 4 (September, October, November, 1942).

89. Bush, S. E., Wood, W. P., and Rote, F. B. "Progress Report on Surface Hardening of Pearlitic Malleable Irons," *Transactions*, American Foundrymen's Society, Vol. 57 (1949), p. 367.

90. Joseph, C. F. Central Foundry Division, General Motors Corporation, private communication, March 15, 1957.

91. Lindsay, R. W., and Atherton, J. E. "Heat-Treatment Study of Pearlitic Malleable Cast Iron," *American Foundryman*, Vol. 8, No. 2 (September, 1945).

92. Heine, R. W. "Hardenability of Pearlitic Malleable Iron," *Transactions*, American Foundrymen's Society, Vol. 66, 1958.

93. Boyes, D. L. *The Commercial Market for Pearlitic Malleable Cast Iron*, Cambridge, Massachusetts Institute of Technology, 1941.

94. Joseph, C. F. "Pearlitic Malleable Iron, Its Properties and Expanded Uses," *S.A.E. Preprint No. 207*, January, 1954.

95. Cameron, J. A. "Oxidation of Plain, Alloyed and Ductile Irons at 1300 Degrees F," *Corrosion*, Vol. 10, No. 9 (September, 1954).

96. Lorig, C. H., and Adams, R. R. *Copper as an Alloying Element in Steel and Cast Iron*, New York, McGraw-Hill Book Company, Inc., 1948.

97. Lorig, C. H. "Copper Additions to Malleable Cast Iron," *Foundry*, Vol. 62, No. 8 (August, 1934).

98. Elsea, A., and Lorig, C. H. "The Effect of Copper Content and Low Temperature Pretreatment of Some White Irons on Malleableization," *Transactions*, American Foundrymen's Association, Vol. 50 (1942), p. 1032.

99. Smith, C. S., and Palmer, E. W. "The Precipitation-hardening of Copper Steels," *Transactions*, American Institute of Mining and Metallurgical Engineers, Vol. 105 (1933).

100. Wolf, F. L., and Miesse, L. A. "Corrosion of Malleable Iron," *Proceedings*, American Society for Testing Materials, Vol. 31, Part II (1931).

101. Archer, R. S., Briggs, J. Z., and Loeb, C. M., Jr. *Molybdenum Steels-Irons-Alloys*, New York, Climax Molybdenum Company (Hudson Press), 1948.

102. Lansing, J. H. "Malleable Iron Castings," *Product Engineering*, Vol. 18, No. 6 (June, 1947).

103. Kanter, J. J., and Guarnieri, Glen. "Some Creep Studies on Cupola Malleable Cast Iron," *Proceedings,* American Society for Testing Materials, Vol. 42 (1942).

104. Bishop, H. F., and Pellini, W. S. "Solidification of Metals," *Foundry,* Vol. 80, No. 2 (February, 1952).

105. Drop Forgings Association. *Standard Practices and Tolerances for Impression Die Forgings,* Cleveland, 1955.

106. Bray, John L. *Ferrous Production Metallurgy,* New York, John Wiley and Sons, Inc., 1942.

107. Robiette, A. G. E. *Electric Melting and Smelting Practice,* London, Charles Griffin and Company, Ltd., 1955.

108. Bolton, John W. *Gray Cast Iron,* Cleveland, Penton Publishing Company, 1937.

109. Heine, R. W., and Rosenthal, P. C. *Principles of Metal Casting,* New York, McGraw-Hill Book Company, Inc., 1955.

110. Campbell, Harry S. *Metal Castings,* New York, John Wiley and Sons, Inc., 1936.

111. American Foundrymen's Society. *The Cupola and Its Operation,* Chicago, 1954.

112. Chvorinov, N. "Control of the Solidification of Castings by Calculation," *Foundry Trade Journal,* Vol. 61, No. 1199 (August 10, 1939).

113. Ruddle, R. W. *The Solidification of Castings, A Review of the Literature,* London, Institute of Metals, 1950.

114. Stoughton, Bradley. *The Metallurgy of Iron and Steel,* New York, McGraw-Hill Book Company, Inc., 1934.

115. Campbell, James S. Jr. *Casting and Forming Practices in Manufacturing,* New York, McGraw-Hill Book Company, Inc., 1950.

116. Albrecht, W. M. Chain Belt Company, private communication, February 7, 1958.

117. Mannweiler, Gordon B. Eastern Malleable Iron Company, private communication, January 22, 1958.

118. American Foundrymen's Society. *Foundry Sand Handbook,* Chicago, 1952.

119. Crannell, R. W. Lehigh Foundries Company, private communication, January 30, 1958.

120. Bean, W. R., and Jaeschke, W. R. "Periodic Malleable Annealing Furnaces," *Transactions,* American Foundrymen's Association, Vol. 50 (1942), p. 39.

121. Cox, R. E. "Annealing Malleable Castings in Elevator Furnace," *Foundry,* Vol. 69, No. 4 (April, 1941).

122. Anderson, R. J. "Malleable Annealing in the Dressler or Tunnel-type Kiln," *Transactions,* American Foundrymen's Association, Vol. 50 (1942), p. 50.

123. Cherry, R. M. "Electric Furnace Annealing of Malleable Iron," *Transactions,* American Foundrymen's Association, Vol. 50 (1942), p. 67.

124. Weedfall, C. W. "Design of Straightening Equipment for Malleable Iron Castings," *Transactions,* American Foundrymen's Association, Vol. 46 (1938), p. 713.

125. Curtiss-Wright Corporation—United States Air Force. "Increased Production, Reduced Costs through a Better Understanding of the Machining Process and Control of Materials, Tools, Machines," (United States Air Force Machinability Report), Woodridge, New Jersey, Curtiss-Wright Corporation, 1950.

126. Woldman, N. E., and Gibbons, R. C. *Machinability and Machining of Metals,* New York, McGraw-Hill Book Company, Inc., 1951.

127. American Society of Tool Engineers. *Tool Engineers Handbook,* New York, McGraw-Hill Book Company, Inc., 1949.

128. Boston, O. W., Moir, H. L., Oldacre, W. H., and Slaughter, E. M. "Machinability Ratings of Metals and Cutting Fluid Recommendations," *Metal Progress,* Vol. 44, No. 4 (October, 1943).

129. *Metal Cutting Tool Handbook.* "Machinability Rating," New York, Metal Cutting Tool Institute, 1954.

130. *1954 SAE Handbook.* "Estimated Physical Properties of Hot-Rolled and Cold-Finished Carbon Steel Bars," New York, Society of Automotive Engineers, Inc., 1954.

131. Republic Steel Corporation. *Handbook of Machining Data for Users of Republic Cold Finished Bars,* Massillon, Ohio, Republic Steel Corporation, Union Drawn Steel Division, 1955.

132. Boston, O. W. *Metal Processing,* New York, John Wiley and Sons, Inc., 1951.

133. Paschkis, V. "Temperature Distribution in the Workpiece: Study by Means of Electric Analogy," Research Report No. 1, American Society of Tool Engineers Research Fund, Detroit, November, 1954.

134. Hollander, M. B., and Englund, J. E. "A Thermocouple-Technique Investigation of Temperature Distribution in the Workpiece during Metal Cutting," Research Report No. 7, American Society of Tool Engineers Research Fund, Detroit, July, 1957.

135. Battelle Memorial Institute. "An Evaluation of the Present Understanding of Metal Cutting," Research Report No. 20, American Society of Tool Engineers Research Fund, Detroit, August, 1958.

136. Gideon, D., Simon, R., and Grover, H. "The Mechanism of Chip Formation," Research Report No. 9, American Society of Tool Engineers Research Fund, Detroit, May, 1958.

137. Gideon, D., Simon, R., and Grover, H. "Some Thermal and Physical Aspects of Cutting," Research Report No. 10, American Society of Tool Engineers Research Fund, Detroit, May, 1958.

138. Weiner, J. H. "Shear-Plane Temperature Distribution in Orthogonal Cutting," *Transactions*, American Society of Mechanical Engineers, Vol. 77 (1955).

139. Rapier, A. C. "A Theoretical Investigation of the Temperature Distribution in the Metal Cutting Process," *British Journal of Applied Physics*, Vol. 5, No. 11 (November, 1954).

140. Trent, E. M. "Some Factors Affecting Wear on Cemented Carbide Tools," *Proceedings*, Institute of Mechanical Engineers, Vol. 66 (1952).

141. "Some Recent Concepts of Machinability." *Lubrication*, Vol. 38, No. 7 (July, 1952).

142. Sudholz, L. H. "Cutting Fluids, Fundamentals and Laboratory Evaluation," *Lubrication Engineering*, Vol. 13, No. 5 (September, 1957).

143. Bridgman, P. W. "Effects of High Shearing Stress Combined with High Hydrostatic Pressure," *Physical Review*, Vol. 48, No. 10 (May, 1935).

144. Bridgman, P. W. "Shearing Phenomena at High Pressures, Particularly in Inorganic Compounds," *Proceedings*, American Academy of Arts and Sciences, Vol. 71 (1937).

145. Bridgman, P. W. "Flow Phenomena in Heavily Stressed Metals," *Journal of Applied Physics*, Vol. 8, No. 5 (May, 1937).

146. Bridgman, P. W. "On Torsion Combined with Compression," *Journal of Applied Physics*," Vol. 14, No. 6 (June, 1943).

147. "Cutting Fluids Poise for New Sales Splash." *Chemical Week*, Vol. 81, No. 16 (October 19, 1957).

148. Shaw, M. C., Pigott, J. D., and Richardson, L. P. "The Effect of the Cutting Fluid upon Chip-Tool Interface Temperature," *Transactions*, American Society of Mechanical Engineers, Vol. 73 (1951).

149. Epifanov, G. I., Pleteneva, N. A., and Rebinder, P. A. "Mechanism of Action of Active Agents in the Cutting of Metals," *Doklady Akademii Nauk USSR*, Vol. 97 (1954), Brutcher Translation No. 3424.

150. Epifanov, G. I. "Influence of Active Agents on Chip Elements," *Doklady Akademii Nauk USSR*, Vol. 104 (1955), Brutcher Translation No. 3719.

151. Opitz, H. "Temperature Field of a Turning Tool and the Reactions of the Zone of Contact," *Microtecnic*, Vol. 8, No. 4 (April, 1954).

152. Roeser, W. F., and Wensel, H. T. "High Purity Iron," *Journal of Research,* National Bureau of Standards No. 26 (1941), p. 273.

153. Lea, F. C. "The Effect of Temperature on some of the Properties of Metals," *Proceedings,* Institute of Mechanical Engineers (London) 1922, p. 885.

154. Hatfield, W. H. "The Application of Science to the Steel Industry," Section Effect of Temperature Upon Steels, *Transactions,* American Society for Steel Treating, Vol. 16, 121 (1929).

155. Hopkins, B. E., Jenkins, G. C. H., and Stone, H. E. C. "Production of High-Purity Iron and Iron Alloys on a 25-lb. Scale," *Journal* Iron and Steel Institute (British) August, 1951, page 377.

156. Rees, W. P., Hopkins, B. E., and Tipler, H. R. "Tensile and Impact Properties of Iron and Some Alloys of High Purity," *Journal* Iron and Steel Institute (British) October, 1951, p. 157.

157. Bain, Edgar C. *Functions of Alloying Elements in Steel,* American Society for Metals, Cleveland, Ohio, 1939.

158. Schwartz, H. A. *Foundry Science,* Pitman, 1950.

159. Porter, L. F., and Rosenthal, P. C. "Factors Affecting Fluidity of Cast Iron," *Transactions,* American Foundrymen's Society, Vol. 60 (1952), p. 725.

160. Lange, E. A., and Heine, R. W. "Effects of Melting Furnace Atmosphere on Casting Properties and Annealability of Malleable Iron," *Transactions,* American Foundrymen's Society, Vol. 61 (1953), p. 107.

161. Lange, E. A., and Heine, R. W. "Effects of Melting Furnace Atmosphere on Fluidity, Hot Tearing Tendency, and Other Properties of Malleable Iron," *Transactions,* American Foundrymen's Society, Vol. 60 (1952), p. 169.

162. Kempka, G. E., and Heine, R. W. "Some Effects of Melting Furnace Atmospheres on Tensile Properties and Annealability of Malleable Iron," *Transactions,* American Foundrymen's Society, Vol. 62 (1954), p. 53.

163. Brick, R. M., and Phillips, A. *Structure and Properties of Alloys,* McGraw-Hill, New York, New York, 1942.

164. Schwartz, H. A., and Hedberg, J. D. "The Location of Alloying Metals in White Cast Iron," *Transactions,* American Society for Metals, Vol. 40 (1948), p. 223.

165. Rehder, J. E. "Effects of Temperature and Silicon Content on First Stage Annealing of Blackheart Malleable Iron," *Transactions,* American Foundrymen's Society, Vol. 57 (1949), p. 173.

166. Rehder, J. E. "The Relative Effects of Chromium and Silicon Contents on Rate of Anneal of Blackheart Malleable Iron," *Transactions,* American Foundrymen's Society, Vol. 59 (1951), p. 244.

167. SCHWARTZ, H. A., and BOCK, W. K. "Effect of the Common Alloying Elements on the Tensile Properties of Malleable Iron," *Transactions,* American Foundrymen's Society, Vol. 56 (1948), p. 458.

168. MARSHALL, L. H. "Embrittlement of Malleable Cast Iron Resulting from Heat Treatment," *U.S. Bureau of Standards Technologic Paper,* Vol. 17 (1923), p. 677. U.S. Patent, 1,553,907, September 15, 1925.

169. BEAN, W. R. "Deterioriation of Malleable in the Hot Dip Galvanizing Process," *Transactions,* American Institute of Mining and Metallurgical Engineers, Vol. 49 (1923), p. 895.

170. LORIG, C. H., and SMITH, C. S. "Effect of Copper in Malleable Iron," *Transactions,* American Foundrymen's Association, Vol. 43 (1934), p. 211.

171. KIKUTA, T. "Effect of Thermal Treatment on the Characteristics of Blackheart Malleable Iron," *Transactions,* American Foundrymen's Association, Vol. 40 (1932), p. 401. U.S. Patent, 1,692,842, Nov. 27, 1928.

172. FORBES, D. P. "Eliminates White Fracture in Malleable," *Foundry,* Vol. 57, No. 7 (1929), p. 613.

173. SCHWARTZ, H. A. "Rust Resistant Iron," U.S. Patent No. 1,535,549 (April 28. 1925).

174. SMITH, C. S., and PALMER, E. W. *Transactions,* American Institute Mining Engineers, Vol. 116 (1935) p. 363.

175. SCHWARTZ, H. A. "Chemical Composition of Malleable Iron," *Transactions,* American Foundrymen's Association, Vol. 54 (1946), p. 101.

176. HEINE, R. W. "Some Effects of Deoxidizing Additions on Foundry Malleable Irons," *Transactions,* American Foundrymen's Society, Vol. 58 (1950), p. 277.

177. BOEGEHOLD, A. L. U.S. Patent No. 1,707,753 (April 2, 1929), "Malleable Iron Alloy."

178. *Malleable Division, Sub-Committee Report.* "Controlled Atmosphere Annealing of Malleable Iron." *Transactions,* American Foundrymen's Society, Vol. 57 (1949), p. 562.

179. MCMILLAN, W. D. "Furnace Atmospheres for Malleable Annealing," *Transactions,* American Foundrymen's Society, Vol. 58 (1950), p. 365.

180. CULLEN, O. E., and LIGHT, R. J. "Malleable Cast Iron—Annealing Furnaces and Atmosphere," *Transactions,* American Foundrymen's Society, Vol. 59 (1951), p. 494.

181. BROWN, F., and HAWKES, M. F. "Effect of Hydrogen on Graphitization," *Transactions,* American Foundrymen's Society, Vol. 60 (1952), p. 635.

182. Bryce, J. T., Hernandez, A., and Rote, F. B. "Influence of Furnace Atmosphere on the Annealing of Malleable Iron," *Transactions,* American Foundrymen's Society, Vol. 61 (1953), p. 291.

183. Schwartz, H. A. "The Kinetics of Graphitization in White Cast Iron," *Transactions,* American Society for Metals, Vol. 30 (1942), p. 1328. "*The Principles of Graphitization,*" *Transactions,* American Foundrymen's Society, Vol. 50 (1942), p. 1.

184. Schulte, F. J. "Metallurgical Considerations in the Gaseous Annealing of Whiteheart Malleable Iron," *Journal of Research,* British Cast Iron Research Association, Vol. 3 (1951), p. 883.

185. Brown, F. "Effect of Prebaking in Malleablizing Iron," *Transactions,* American Foundrymen's Society, Vol. 62 (1954), pp. 264-266.

186. Massari, S. C. "Graphitizing Behavior of White Iron," *American Foundryman,* Vol. 15, No. 5 (1949), p. 67.

187. Bock, W. K. "Effect of Plastic Deformation of Hard Iron on Subsequent Annealing," *Transactions,* American Foundrymen's Society, Vol. 62 (1954), pp. 579-582.

188. Schwartz, H. A., Hedberg, J. D., and Eriksen, R. "Subcritical Isothermal Graphitization," *Transactions,* American Foundrymen's Society, Vol. 58 (1950), p. 578.

189. Bush, S. H., Wood, W. P., and Rote, F. B. "Surface Hardening of Pearlitic Malleable Irons," *Transactions,* American Foundrymen's Society, Vol. 58 (1950), p. 108.

190. Lansing, James H. "Practical Operating Phases of Melting," Symposium on Malleable Melting, *Transactions,* American Foundrymen's Association, Vol. 51 (1943), pp. 387-400.

191. Schwartz, H. A., and Hedberg, J. D. "Graphitization of Rims in Malleable Iron," *Transactions,* American Foundrymen's Society, Vol. 62 (1954), p. 282.

192. Morrogh, H., and Williams, W. J. "Graphite Formation in Cast Irons and in Nickel-Carbon and Cobalt-Carbon Alloys," *Journal* Iron and Steel Institute (British), Vol. 155 (1947), pp. 327-371.

193. Donoho, C. "Producing Nodular Graphite with Magnesium," *American Foundryman,* Vol. 15, No. 2 (February, 1949), p. 30.

194. Morral, F. R. "Nodular Iron—A Bibliography," *American Foundryman,* Vol. 18, No. 1 (July, 1950), p. 61.

195. Tilley, M. "Effect of Oxidation Rates on Graphitization of Cupola Melted Malleable," *Foundry,* Vol. 80, No. 11 (November, 1952), p. 108.

196. Hall, A. M. "Graphitization in Steel," *Materials and Methods,* Vol. 40, No. 5 (November, 1954), p. 96.

197. Brown, B. F. "Subcritical Graphitization Can be Controlled," *Iron Age,* August 31, 1950, p. 64.

198. Austin, C. R., and Norris, B. S. "Effects of Small Amounts of Alloying Elements on Graphitization of Pure Hypereutectoid Steels," *Transactions,* American Society for Metals, Vol. 30 (1942), p. 425.

199. Schwartz, H. A. Unpublished work, 1949.

200. Shnay, R. C., Wilson, J. E., and Rehder, J. H. "Effects of Trace Amounts of Tin, Lead, and Antimony on the Annealing of Blackheart Malleable Iron," *Transactions,* American Foundrymen's Society, Vol. 63 (1955), p. 457.

201. Bunin, K. P., and Chernovol, A. V. "The Form of Nodules of Temper Carbon," *Doklady Akademii Nauk USSR,* Vol. 95 (1954), p. 785. (Digested in *Metal Progress,* Vol. 68, No. 2 (August, 1955), p. 80).

202. Rehder, J. E. "Effect of Manganese-Sulphur Ratio on the Rate of Anneal of Blackheart Malleable Iron," *Transactions,* American Foundrymen's Society, Vol. 56 (1948), pp. 138-151.

203. Lindsay, R. W., and Atherton, J. E. "Heat Treatment Study of Pearlitic Malleable Cast Iron," *Transactions,* American Foundrymen's Association, Vol. 53 (1945), pp. 301-306.

204. Cowan, R. J. "The Heat Treatment of Malleable Iron," *Transactions,* American Foundrymen's Association, Vol. 48 (1940), pp. 283-303.

205. Rote, F. B., Chojnowski, E. F., and Bryce, J. T. "Malleable Base Spheroidal Iron," *Transactions,* American Foundrymen's Society, Vol. 64 (1956), pp. 197-208.

206. "Armasteel"—General Motors Corporation (1954).

207. Technical Outlook, *Steel,* June 13, 1955, p. 107.

208. Sears, G. W., and Brenner, S. S. "Metal Whiskers," *Metal Progress,* Vol. 70, No. 5 (November, 1956), pp. 85-89.

209. Schneidewind, R. Discussion of J. H. Rehder's paper, "Effect of Manganese-Sulfur Ratio on the Rate of Anneal of Blackheart Malleable Iron," *Transactions,* American Foundrymen's Society, Vol. 56 (1948), pp. 146-148.

210. Porter, L. F., and Rosenthal, P. C. "Effect of Sulphur on Fluidity of Gray Cast Iron," *Transactions,* American Foundrymen's Society, Vol. 60 (1952), p. 611.

211. Sandoz, G. A., Howells, N. C., Bishop, H. F., and Pellini, W. S. "Notch Ductility of Malleable Irons," *Transactions,* American Society for Metals, Vol. 49 (1957), pp. 204-241.

212. McClure, N. C., Khan, A. U., Grady, D. D., and Womochel, H. L. "Inoculation of Gray Cast Iron—Relative Effectiveness of Some Silicon Alloys and Active Metals as Ladle Additions," *Transactions,* American Foundrymen's Society, Vol. 65 (1957), p. 340.

213. Gilbert, G. N. J. "Temper Embrittlement in Nodular Iron," *Transactions,* American Foundrymen's Society, Vol. 65 (1957), p. 49.

214. Sandelin, R. W. "Some Observations on Galvanizing Embrittlement of Malleable Iron," *Transactions,* American Foundrymen's Society, Vol. 65 (1957), p. 409.

215. Kempka, G. E. "Embrittlement, Toughening, and Subcritical Thermal Treatment of Malleable Iron," *Transactions,* American Foundrymen's Society, Vol. 63 (1955), p. 675.

216. Bremer, E. "Embrittlement in Malleable is Avoided," *Foundry,* Vol. 54 (March, 1926), pp. 212-215.

217. Leroyer, H. "Influence of Thermal Treatment on the Properties of Blackheart Malleable," Bulletin de l'Association Technique de Fonderie, Vol. 10 (May, 1936), pp. 173-177.

218. LaPlance, H. "Les Principales Maladies de la Malleable a Coeur Noir et Leur Diagnostic Micrographique," *Fonderie,* No. 14 (March, 1947), p. 507, 564-581.

219. Boegehold, A. L. "A New Composition for Fast Malleable Iron," *Metal Progress,* American Society for Metals, Vol. 70, No. 4 (October, 1956), pp. 73-74.

220. Controlled Annealing Committee Report. "Planning for Heat Treating in Malleable Iron Foundries," *Modern Castings,* Vol. 31, No. 2 (1957), pp. 39-54.

221. Lownie, H. W. "Use of Pig Iron in Iron Foundries," *Transactions,* American Foundrymen's Society, Vol. 64 (1956), pp. 119-121.

222. Bleil, H. E., and Varga, J., Jr. "Influence of Zirconium on Malleablization of White Iron," *Foundry,* Vol. 78, No. 10 (1950), pp. 94-99.

223. Eckman, H. A., and Maack, Henry W. U.S. Patent No. 2,450,395 (September 28, 1948), "Malleable Cast Iron."

224. Eckman, H. A., and Maack, H. W. U.S. Patent No. 2,579,452 (December 25, 1951), "Malleable Iron with Boron and Bismuth."

225. Boegehold, A. L. U.S. Patent No. 2,331,886 (October 19, 1943), "Alloy Malleable Iron."

226. Boegehold, A. L. U.S. Patent No. 2,370,225 (February 27, 1945), "Malleable Iron."

227. Crome, L. C. U.S. Patent No. 2,595,567 (May 6, 1952), "Process for Producing Malleable Iron Castings."

228. Heine, H. J. "Machinability and Microstructure," *American Foundryman* (January, 1954), Vol. 25, No. 1, pp. 58-61.

229. Donoho, C. K. "Austenitic Malleable Iron—A New Ferrous Material," *Materials & Methods,* September, 1947, p. 85.

230. SCHWARTZ, H. A. "Some Principles of Melting Malleable Iron," *Transactions,* American Foundrymen's Association, Vol. 51 (1943), pp. 261-271.

231. HEINE, R. W. "Oxidation—Reduction Principles Controlling the Composition of Molten Cast Iron," *Transactions,* American Foundrymen's Society, Vol. 59 (1951), p. 121.

232. ZRIMSEK, A. H., BELTER, E. H., and HEINE, R. W. "Effects of Charge Proportions, Furnace Atmosphere, Flow Rate, and Melt-Down Time on Properties of Malleable Iron," *Transactions,* American Foundrymen's Society, Vol. 64 (1956), pp. 72-81.

233. LAPOUR, F. L. "Malleable Duplexing Melting Control," *American Foundryman* (April, 1955) pp. 38-40.

234. EMERY, L. E. "Malleable Melting Control," *American Foundryman* (October, 1954), pp. 42-45.

235. EMERY, L. E. "Start Duplex Malleable Control with Raw Materials," *American Foundryman* (June, 1955), pp. 90-95.

236. JACOBS, F. W., and LAWRENCE, J. S., JR. "Correlation of Air Furnace Bottom Temperature to Refractory and Operating Practice in a Cupola-Air Furnace Duplex System," *Transactions,* American Foundrymen's Society, Vol. 61 (1953), p. 479.

237. JACOBS, F. W., and ASHLEY, E. C. "Correlation of Air Furnace Bottom Temperature to Refractory and Operating Practice in a Cupola-Air Furnace Duplex System," *Transactions,* American Foundrymen's Society, Vol. 62 (1954), p. 429.

238. REHDER, J. E. "Notes on Air Furnace Design and Operation," *Transactions,* American Foundrymen's Society, Vol. 61 (1953), p. 516.

238. MEYER, C. W. "Refractory Practice as Applied to Malleable Duplexing," *Transactions,* American Foundrymen's Society, Vol. 60 (1952), p. 300.

240. TECHNICAL BULLETINS, Nos. 182, 309, 333, 412, 413, 518, Malleable Founders' Society.

241. CORBEAU, W. C. "Air Furnace Refractory Practice on Cupola-Air Furnace Duplexing," *Transactions,* American Foundrymen's Society, Vol. 60 (1952), p. 570.

242. NIELSEN, E. H. "Melting Malleable Iron with Pulverized Coal and Oil as Fuel," *Transactions,* American Foundrymen's Society, Vol. 64 (1956), p. 242.

243. *Symposium on Malleable Melting—Transactions,* American Foundrymen's Association, Vol. 51 (1943), pp. 261-416. Note: see individual references.

SCHWARTZ, H. A. "Some Principles of Melting Malleable Iron," pp. 261-271.

KELLY, LEO J. "Open-Hearth Furnace for Production of Malleable Castings," pp. 272-276.

MORRISON, CHARLES. "Cupola Electric Furnace Duplexing of Malleable Iron," pp. 277-311.

DURR, J. A. "Control of Powdered-Coal-Fired Melting Furnaces," pp. 312-326.

WURSCHER, F. J. "The Cupola-Air Furnace Duplex Process for Production of Malleable Cast Iron," pp. 327-342.

VAN LANTSCHOOT, AUGUST. "Melting Malleable Iron with Oil in the Air Furnace," pp. 343-364.

ZEUNIK, W., and MASON, KENNETH. "Brackelsberg Furnace Melting of Malleable Iron," pp. 365-376.

MAACK, H. W. "Melting Cupola Malleable Iron," pp. 377-386.

LANSING, J. H. "Practical Operating Phases of Melting," pp. 387-400.

BRASHARES, C. A. "Malleable Foundry Refractory Practice," pp. 401-416.

244. SMITH, L. W. C., BACH, B. B., and DAWSON, J. V. "Estimation and Influence of Gaseous Elements in Cast Iron," *Foundry Trade Journal* (British), Vol. 96 (1954), p. 233.

245. SEMRAU, C. F. "Construction and Operation of Coal Fired Air Furnace," *American Foundryman* (August, 1953), Vol. 24, No. 2, p. 34.

246. COGHLIN, F., JR. "Construction and Operation of an Oil-Fired Malleable Iron Holding Furnace," *Transactions,* American Foundrymen's Society, Vol. 56 (1948), p. 518.

247. COGHLIN, F., JR. "Rigid Controls and Standards Improve Duplexing Operations," *American Foundryman* (September, 1951), Vol. 20, No. 3, p. 24.

248. BREMER, E. "Melting Control Pays Off in Malleable Foundry," *Foundry,* Vol. 79, No. 10 (October, 1951), p. 98.

249. POLLACK, C. "Low Frequency Induction Melting Employed in Malleable Foundry," *Foundry,* Vol. 81, No. 7 (July, 1953), p. 108.

250. REESE, D. J., ROTE, F. B., and CONGER, G. A. SAE Preprint No. 692, January, 1952. "Effect of Chemistry and Section Size on Properties of Ductile Iron."

251. SCHWARTZ, H. A. "Making Malleable Iron Castings." U.S. Patent No. 1,688,438 (October 23, 1928).

252. CLOUGH, W. R., and SHANK, M. E. "The Deformation and Rupture of Gray Cast Iron," *Transactions,* American Society for Metals, Vol. 49 (1957), pp. 241-262.

253. BEISER, C. A., and EVANS, E. B. "You Can Quench-Age Malleable Iron," *Modern Castings,* Vol. 30, No. 4 (October, 1956), p. 39.

254. Thyberg, Bertil. "Progress in the Development of High Duty Malleable Cast Iron," *Foundry Trade Journal* (British), Vol. 103 (1957), p. 213-224.

255. Roberts, E. C. "Effect of Manganese on the Curie Point of Cementite," *Transactions,* American Society for Metals, Vol. 50 (1958), pp. 129-140.

256. Tsutsumi, N. "The Effects of Alloying Elements on the Graphitization of White Irons containing Small Percentage of Chromium," Report of the Castings Research Laboratory, Waseda University, No. 4, 1953.

257. Tsutsumi, N. "On Austenitic Malleable Iron," Report of the Castings Research Laboratory, Waseda University, No. 6, 1955.

258. Tsutsumi, N. "Some Experiments on the Embrittlement of Malleable Iron," Report of the Castings Research Laboratory, Waseda University, No. 5, 1954.

259. Tsutsumi, N. "Some Experiments on the Embrittlement of Malleable Iron, Report II," Report of the Castings Research Laboratory, Waseda University, No. 8, 1957.

260. Scheurer, W. "Scale Formation on Steel," *Stahl und Eisen,* July 31, 1952.

261. Committee 6D Report. "Malleable Iron Microstructures, Effect and Cause," *Transactions,* American Foundrymen's Society, Vol. 66 (1958), p. 166-176.

262. Smith, L. W. L. *Journal of Research and Development,* British Cast Iron Research Association, Vol. 5 (1954), p. 173-179.

263. Dawson, J. V., and Smith, L. W. L. "Gases in Cast Iron with Special Reference to Pickup of Hydrogen in Sand Molds," *Transactions,* American Foundrymen's Society, Vol. 66 (1958), p. 17-30.

264. Green, P. W. "Salt Bath Heat Treatment vs. Quench and Temper Standard and Pearlitic Malleable Iron," *Transactions,* American Foundrymen's Society, Vol. 66 (1958), p. 507-512.

265. Lytle, A. R. "Whiskers Research," *Journal,* Society of Automotive Engineers, Paper No. 56R, Vol. 67 (1959), No. 5.

266. Editorial, *Steel,* July 7, 1958, p. 83.

267. Gray Iron Castings Handbook, Gray Iron Founders' Society, Cleveland (1958).

268. Schwartz, H. A., Johnson, H. H., and Junge, C. H. "Retarding Effect of Certain Metallic Elements on Graphitization," *Transactions,* American Society for Metals, Vol. 25 (1937), No. 2, p. 609.

269. Hall, R. "Alloys for Malleable Iron," *Iron Age,* Vol. 132 (1933), p. 8.

270. Soehnchen, E. "Alloyed Malleable Iron (Legierter Temperguss)," *Z.f.d. Gesamte Giessereipraxis,* Vol. 54 (1933), Nos. 15-16, p. 151.

271. SCHWARTZ, H. A., FIORDALIS, V., FISHER, J. L., SHUMER, J. R., and TRINTER, M. J. "Accelerating Effect of Certain Metallic Elements on Graphitization," *Transactions,* American Society for Metals, Vol. 28 (1940), No. 1, page 143.
272. COMMITTEE ON TRACE ELEMENTS. "Effect of Trace Elements on Malleable Irons," Bulletin No. 548, Malleable Founders Society, April, 1959.
273. SANDOZ, G. "The Partitioning of Alloying Elements in Malleable Irons," Report, U.S. Naval Research Laboratory, No. 5268 (Feb., 1959).
274. McCARROLL, R. H., and VENNERHOLM, G. U.S. Patent No. 1,871,545.
275. LARSON, W. B., JOSEPH, C. F., WEBBERE, F. J., and THOMSON, R. F. "General Motors Describes Centrasteel," *Modern Castings,* Vol. 35 (1959), No. 3, p. 47.
276. GRANGE, R. A., LAMBERT, V. E., and HARRINGTON, J. J. "Effect of Copper on the Heat Treating Characteristics of Medium-Carbon Steel," *Transactions,* American Society for Metals, Vol. 51 (1959), p. 377-393.
277. LOPER, C. R., JR., and HEINE, R. W. "Mottling in Heavy Section White Iron Castings," *Transactions,* American Foundrymen's Society, Vol. 67 (1959), p. 380.
278. HEINE, R. W. "Melting Variables Effect on Malleable Iron Properties," *Transactions,* American Foundrymen's Society (1959).
279. "Manual on Fatigue Testing," American Society for Testing Materials. Special Technical Publication No. 91 (1949).
280. "A Tentative Guide for Fatigue Testing and the Statistical Analysis of Fatigue Data," American Society for Testing Materials. Special Technical Publication No. 91-A (1958).
281. "Symposium on Statistical Aspects of Fatigue," American Society for Testing Materials. Special Technical Publication No. 121 (1951).
282. BATTELLE MEMORIAL INSTITUTE STAFF. "Prevention of Failure of Metals Under Repeated Stress," John Wiley and Sons, New York (1946).
283. "Definitions Relating to Methods of Testing," American Society for Testing Materials, Specification E6-58aT, Book of Standards, Part 3, 1958, p. 182.
284. Unpublished research by member company (1958).
285. KROUSE, G. N. "A High-Speed Fatigue Testing Machine and Some Tests of Speed Effect on Endurance Limit," American Society for Testing Materials, Preprint No. 34, 1934.
286. SCHWARTZ, H. A., and BOCK, W. K. "Notch Fatigue of Malleable Iron," National Malleable and Steel Castings Company (unpublished), Research Report No. 3-11, January 13, 1950.

287. **Oberg**, T. T., and **Johnson**, J. B. "Fatigue Properties of Metals Used in Aircraft Construction at 3450 and 10,600 cycles," Proceedings, American Society for Testing Materials, V. 37, Part II (1937), p. 205.

288. **Jackson**, L. R., and **Pochapsky**, T. E. "The Effect of Composition on the Fatigue Strength of Decarburized Steel," *Transactions*, American Society for Metals, V. 39 (1947), p. 45-60.

289. **Dolan**, T. J., and **Yen**, C. S. "Some Aspects of the Effect of Metallurgical Structure on Fatigue Strength and Notch-Sensitivity of Steel," *Proceedings*, American Society for Testing Materials, V. 48 (1948), p. 664-695.

290. **Moore**, H. F. "A Study of Size Effect and Notch Sensitivity in Fatigue Tests of Steel," *Proceedings*, American Society for Testing Materials, Vol. 45 (1945), p. 507-531.

291. **Shinn**, D. A., **Oberg**, T. T., and **Johnson**, J. B. "Aluminum-Alloy Aircraft Extrusions," Army Air Force, *Technical Report*, No. 5228, 1954.

292. **After Schneidewind**, R. and **Reese**, D. J. "Pearlitic Malleable Irons, Plain and Alloyed," *Transactions*, American Foundrymen's Society, Vol. 56 (1948), p. 427.

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FUNCTIONS OF NUMBERS

No.	Square	Cube	Square Root	Cube Root	Logarithm	1000 × Reciprocal	No. = Diameter	
							Circum.	Area
.01	.0001	.000001	0.1000	0.2154	$\bar{2}.00000$	100000.000	.03142	.000079
.02	.0004	.000008	0.1414	0.2714	$\bar{2}.30103$	50000.000	.06283	.000314
.03	.0009	.000027	0.1732	0.3107	$\bar{2}.47712$	33333.333	.09425	.000707
.04	.0016	.000064	0.2000	0.3420	$\bar{2}.60206$	25000.000	.12566	.001257
.05	.0025	.000125	0.2236	0.3684	$\bar{2}.69897$	20000.000	.15708	.001964
.06	.0036	.000216	0.2449	0.3915	$\bar{2}.77815$	16666.667	.18850	.002827
.07	.0049	.000343	0.2646	0.4121	$\bar{2}.84510$	14285.714	.21991	.003849
.08	.0064	.000512	0.2828	0.4309	$\bar{2}.90309$	12500.000	.25133	.005027
.09	.0081	.000729	0.3000	0.4481	$\bar{2}.95424$	11111.111	.28274	.006362
.10	.0100	.001000	0.3162	0.4642	$\bar{1}.00000$	10000.000	.31416	.007854
.11	.0121	.001331	0.3317	0.4791	$\bar{1}.04139$	9090.909	.34558	.009503
.12	.0144	.001728	0.3464	0.4932	$\bar{1}.07918$	8333.333	.37699	.011310
.13	.0169	.002197	0.3606	0.5066	$\bar{1}.11394$	7692.308	.40841	.013273
.14	.0196	.002744	0.3742	0.5192	$\bar{1}.14613$	7142.857	.43982	.015394
.15	.0225	.003375	0.3873	0.5313	$\bar{1}.17609$	6666.667	.47124	.017672
.16	.0256	.004096	0.4000	0.5429	$\bar{1}.20412$	6250.000	.50265	.020106
.17	.0289	.004913	0.4123	0.5540	$\bar{1}.23045$	5882.353	.53407	.022698
.18	.0324	.005832	0.4243	0.5646	$\bar{1}.25527$	5555.556	.56549	.025447
.19	.0361	.006859	0.4359	0.5749	$\bar{1}.27875$	5263.158	.59690	.028353
.20	.0400	.008000	0.4472	0.5848	$\bar{1}.30103$	5000.000	.62832	.031416
.21	.0441	.009261	0.4583	0.5944	$\bar{1}.32222$	4761.905	.65973	.034636
.22	.0484	.010648	0.4690	0.6037	$\bar{1}.34242$	4545.455	.69115	.038013
.23	.0529	.012167	0.4796	0.6127	$\bar{1}.36173$	4347.826	.72257	.041548
.24	.0576	.013824	0.4899	0.6214	$\bar{1}.38021$	4166.667	.75398	.045239
.25	.0625	.015625	0.5000	0.6300	$\bar{1}.39794$	4000.000	.78540	.049087
.26	.0676	.017576	0.5099	0.6383	$\bar{1}.41497$	3846.154	.81681	.053093
.27	.0729	.019683	0.5196	0.6463	$\bar{1}.43136$	3703.704	.84823	.057256
.28	.0784	.021952	0.5292	0.6542	$\bar{1}.44716$	3571.429	.87965	.061575
.29	.0841	.024389	0.5385	0.6619	$\bar{1}.46240$	3448.276	.91106	.066052
.30	.0900	.027000	0.5477	0.6694	$\bar{1}.47712$	3333.333	.94248	.070686
.31	.0961	.029791	0.5568	0.6768	$\bar{1}.49136$	3225.807	.97389	.075477
.32	.1024	.032768	0.5657	0.6840	$\bar{1}.50515$	3125.000	1.00531	.080425
.33	.1089	.035937	0.5745	0.6910	$\bar{1}.51851$	3030.303	1.03673	.085530
.34	.1156	.039304	0.5831	0.6980	$\bar{1}.53148$	2941.177	1.06814	.090792
.35	.1225	.042875	0.5916	0.7047	$\bar{1}.54407$	2857.143	1.09956	.096211
.36	.1296	.046656	0.6000	0.7114	$\bar{1}.55630$	2777.778	1.13097	.101788
.37	.1369	.050653	0.6083	0.7179	$\bar{1}.56820$	2702.703	1.16239	.107521
.38	.1444	.054872	0.6164	0.7243	$\bar{1}.57978$	2631.579	1.19381	.113411
.39	.1521	.059319	0.6245	0.7306	$\bar{1}.59106$	2564.103	1.22522	.119459
.40	.1600	.064000	0.6325	0.7368	$\bar{1}.60206$	2500.000	1.2566	.125664
.41	.1681	.068921	0.6403	0.7429	$\bar{1}.61278$	2439.024	1.2881	.132025
.42	.1764	.074088	0.6481	0.7489	$\bar{1}.62325$	2380.952	1.3195	.138544
.43	.1849	.079507	0.6557	0.7548	$\bar{1}.63347$	2325.581	1.3509	.145220
.44	.1936	.085184	0.6633	0.7606	$\bar{1}.64345$	2272.727	1.3823	.152053
.45	.2025	.091125	0.6708	0.7663	$\bar{1}.65321$	2222.222	1.4137	.159043
.46	.2116	.097336	0.6782	0.7719	$\bar{1}.66276$	2173.913	1.4451	.166190
.47	.2209	.103823	0.6856	0.7775	$\bar{1}.67210$	2127.660	1.4765	.173494
.48	.2304	.110592	0.6928	0.7830	$\bar{1}.68124$	2083.333	1.5080	.180956
.49	.2401	.117649	0.7000	0.7884	$\bar{1}.69020$	2040.816	1.5394	.188574

FUNCTIONS OF NUMBERS

No.	Square	Cube	Square Root		Logarithm	1000 × Reciprocal	No. = Diameter	
							Circum.	Area
.50	.2500	125000	0.7071	0.7937	$\bar{1}.69897$	2000.000	1.5708	.19635
.51	.2601	132651	0.7141	0.7990	$\bar{1}.70757$	1960.784	1.6022	.20428
.52	.2704	140608	0.7211	0.8041	$\bar{1}.71600$	1923.077	1.6336	.21237
.53	.2809	148877	0.7280	0.8093	$\bar{1}.72428$	1886.793	1.6650	.22062
.54	.2916	157464	0.7348	0.8143	$\bar{1}.73239$	1851.852	1.6965	.22902
.55	.3025	166375	0.7416	0.8193	74036	1818.182	1.7279	.23758
.56	.3136	175616	0.7483	0.8243	74819	1785.714	1.7593	.24630
.57	.3249	185193	0.7550	0.8291	$\bar{1}.75587$	1754.386	1.7907	.25518
.58	.3364	195112	0.7616	0.8340	$\bar{1}.76343$	1724.138	1.8221	.26401
.59	.3481	205379	0.7681	0.8387	$\bar{1}.77085$	1694.915	1.8535	.27340
.60	.3600	216000	0.7746	0.8434	77815	1666.667	1.8850	.28274
.61	.3721	226981	0.7810	0.8481	78533	1639.344	1.9164	.29225
.62	.3844	238328	0.7874	0.8527	79239	1612.903	1.9478	.30191
.63	.3969	250047	0.7937	0.8573	79934	1587.302	1.9792	.31173
.64	.4096	262144	0.8000	0.8618	$\bar{1}.80618$	1562.500	2.0106	.32170
.65	.4225	274625	0.8062	0.8662	$\bar{1}.81291$	1538.462	2.0420	.33183
.66	.4356	287496	0.8124	0.8707	$\bar{1}.81954$	1515.152	2.0735	.34212
.67	.4489	300763	0.8185	0.8750	$\bar{1}.82607$	1492.537	2.1049	.35257
.68	.4624	314432	0.8246	0.8794	$\bar{1}.83251$	1470.588	2.1363	.36317
.69	.4761	328509	0.8307	0.8837	$\bar{1}.83885$	1449.275	2.1677	.37393
.70	.4900	343000	0.8367	0.8879	84510	1428.571	2.1991	.38485
.71	.5041	357911	0.8426	0.8921	85126	1408.451	2.2305	.39592
.72	.5184	373248	0.8485	0.8963	85733	1388.889	2.2620	.40715
.73	.5329	389017	0.8544	0.9004	86332	1369.863	2.2934	.41854
.74	.5476	405224	0.8602	0.9045	$\bar{1}.86923$	1351.351	2.3248	.43008
.75	.5625	421875	0.8660	0.9086	87506	1333.333	2.3562	.44179
.76	.5776	438976	0.8718	0.9126	88081	1315.790	2.3876	.45365
.77	.5929	456533	0.8775	0.9166	88649	1298.701	2.4190	.46566
.78	.6084	474552	0.8832	0.9205	89209	1282.051	2.4504	.47784
.79	.6241	493039	0.8888	0.9244	$\bar{1}.89763$	1265.823	2.4819	.49017
.80	.6400	512000	0.8944	0.9283	90309	1250.000	2.5133	.50266
.81	.6561	531441	0.9000	0.9322	90849	1234.568	2.5447	.51530
.82	.6724	551368	0.9055	0.9360	91381	1219.512	2.5761	.52810
.83	.6889	571787	0.9110	0.9398	91908	1204.819	2.6075	.54106
.84	.7056	592704	0.9165	0.9435	$\bar{1}.92428$	1190.476	2.6389	.55418
.85	.7225	614125	0.9220	0.9473	92942	1176.471	2.6704	.56745
.86	.7396	636056	0.9274	0.9510	93450	1162.791	2.7018	.58088
.87	.7569	658503	0.9327	0.9546	93952	1149.425	2.7332	.59447
.88	.7744	681472	0.9381	0.9583	94448	1136.364	2.7646	.60821
.89	.7921	704969	0.9434	0.9619	$\bar{1}.94939$	1123.596	2.7960	.62211
.90	.8100	729000	0.9487	0.9655	95424	1111.111	2.8274	.63617
.91	.8281	753571	0.9539	0.9691	95904	1098.901	2.8589	.65039
.92	.8464	778688	0.9592	0.9726	96379	1086.957	2.8903	.66476
.93	.8649	804357	0.9644	0.9761	96848	1075.269	2.9217	.67929
.94	.8836	830584	0.9695	0.9796	$\bar{1}.97313$	1063.830	2.9531	.69398
.95	.9025	857375	0.9747	0.9830	97772	1052.632	2.9845	.70882
.96	.9216	884736	0.9798	0.9865	98227	1041.667	3.0159	.72382
.97	.9409	912673	0.9849	0.9899	98677	1030.928	3.0473	.73898
.98	.9604	941192	0.9899	0.9933	99123	1020.408	3.0788	.75430
.99	.9801	970299	0.9950	0.9967	$\bar{1}.99564$	1010.101	3.1102	.76977

FUNCTIONS OF NUMBERS

No.	Square	Cube	Square Root	Cube Root	Logarithm	1000 × Reciprocal	No. = Diameter	
							Circum.	Area
1	1	1	1.0000	1.0000	0.00000	1000.000	3.142	0.7854
2	4	8	1.4142	1.2599	0.30103	500.000	6.283	3.1416
3	9	27	1.7321	1.4422	0.47712	333.333	9.425	7.0686
4	16	64	2.0000	1.5874	0.60206	250.000	12.566	12.5664
5	25	125	2.2361	1.7100	0.69897	200.000	15.708	19.6350
6	36	216	2.4495	1.8171	0.77815	166.667	18.850	28.2743
7	49	343	2.6458	1.9129	0.84510	142.857	21.991	38.4845
8	64	512	2.8284	2.0000	0.90309	125.000	25.133	50.2655
9	81	729	3.0000	2.0801	0.95424	111.111	28.274	63.6173
10	100	1000	3.1623	2.1544	1.00000	100.000	31.416	78.5398
11	121	1331	3.3166	2.2240	1.04139	90.9091	34.558	95.0332
12	144	1728	3.4641	2.2894	1.07918	83.3333	37.699	113.097
13	169	2197	3.6056	2.3513	1.11394	76.9231	40.841	132.732
14	196	2744	3.7417	2.4101	1.14613	71.4286	43.982	153.938
15	225	3375	3.8730	2.4662	1.17609	66.6667	47.124	176.715
16	256	4096	4.0000	2.5198	1.20412	62.5000	50.265	201.062
17	289	4913	4.1231	2.5713	1.23045	58.8235	53.407	226.980
18	324	5832	4.2426	2.6207	1.25527	55.5556	56.549	254.469
19	361	6859	4.3589	2.6684	1.27875	52.6316	59.690	283.529
20	400	8000	4.4721	2.7144	1.30103	50.0000	62.832	314.159
21	441	9261	4.5826	2.7589	1.32222	47.6190	65.973	346.361
22	484	10648	4.6904	2.8020	1.34242	45.4545	69.115	380.133
23	529	12167	4.7958	2.8439	1.36173	43.4783	72.257	415.476
24	576	13824	4.8990	2.8845	1.38021	41.6667	75.398	452.389
25	625	15625	5.0000	2.9240	1.39794	40.0000	78.540	490.874
26	676	17576	5.0990	2.9625	1.41497	38.4615	81.681	530.929
27	729	19683	5.1962	3.0000	1.43136	37.0370	84.823	572.555
28	784	21952	5.2915	3.0366	1.44716	35.7143	87.965	615.752
29	841	24389	5.3852	3.0723	1.46240	34.4828	91.106	660.520
30	900	27000	5.4772	3.1072	1.47712	33.3333	94.248	706.858
31	961	29791	5.5678	3.1414	1.49136	32.2581	97.389	754.768
32	1024	32768	5.6569	3.1748	1.50515	31.2500	100.531	804.248
33	1089	35937	5.7446	3.2075	1.51851	30.3030	103.673	855.299
34	1156	39304	5.8310	3.2396	1.53148	29.4118	106.814	907.920
35	1225	42875	5.9161	3.2711	1.54407	28.5714	109.956	962.113
36	1296	46656	6.0000	3.3019	1.55630	27.7778	113.097	1017.88
37	1369	50653	6.0828	3.3322	1.56820	27.0270	116.239	1075.21
38	1444	54872	6.1644	3.3620	1.57978	26.3158	119.381	1134.11
39	1521	59319	6.2450	3.3912	1.59106	25.6410	122.522	1194.59
40	1600	64000	6.3246	3.4200	1.60206	25.0000	125.66	1256.64
41	1681	68921	6.4031	3.4482	1.61278	24.3902	128.81	1320.25
42	1764	74088	6.4807	3.4760	1.62325	23.8095	131.95	1385.44
43	1849	79507	6.5574	3.5034	1.63347	23.2558	135.09	1452.20
44	1936	85184	6.6332	3.5303	1.64345	22.7273	138.23	1520.53
45	2025	91125	6.7082	3.5569	1.65321	22.2222	141.37	1590.43
46	2116	97336	6.7823	3.5830	1.66276	21.7391	144.51	1661.90
47	2209	103823	6.8557	3.6088	1.67210	21.2766	147.65	1734.94
48	2304	110592	6.9282	3.6342	1.68124	20.8333	150.80	1809.56
49	2401	117649	7.0000	3.6593	1.69020	20.4082	153.94	1885.74

FUNCTIONS OF NUMBERS

No.	Square	Cube	Square Root	Cube Root	Logarithm	1000 × Reciprocal	No. = Diameter	
							Circum.	Area
50	2500	125000	7.0711	3.6840	1.69897	20.0000	157.08	1963.50
51	2601	132651	7.1414	3.7084	1.70757	19.6078	160.22	2042.82
52	2704	140608	7.2111	3.7325	1.71600	19.2308	163.36	2123.72
53	2809	148877	7.2801	3.7563	1.72428	18.8679	166.50	2206.18
54	2916	157464	7.3485	3.7798	1.73239	18.5185	169.65	2290.22
55	3025	166375	7.4162	3.8030	1.74036	18.1818	172.79	2375.83
56	3136	175616	7.4833	3.8259	1.74819	17.8571	175.93	2463.01
57	3249	185193	7.5498	3.8485	1.75587	17.5439	179.07	2551.76
58	3364	195112	7.6158	3.8709	1.76343	17.2414	182.21	2642.08
59	3481	205379	7.6811	3.8930	1.77085	16.9492	185.35	2733.97
60	3600	216000	7.7460	3.9149	1.77815	16.6667	188.50	2827.43
61	3721	226981	7.8102	3.9365	1.78533	16.3934	191.64	2922.47
62	3844	238328	7.8740	3.9579	1.79239	16.1290	194.78	3019.07
63	3969	250047	7.9373	3.9791	1.79934	15.8730	197.92	3117.25
64	4096	262144	8.0000	4.0000	1.80618	15.6250	201.06	3216.99
65	4225	274625	8.0623	4.0207	1.81291	15.3846	204.20	3318.31
66	4356	287496	8.1240	4.0412	1.81954	15.1515	207.35	3421.19
67	4489	300763	8.1854	4.0615	1.82607	14.9254	210.49	3525.65
68	4624	314432	8.2462	4.0817	1.83251	14.7059	213.63	3631.68
69	4761	328509	8.3066	4.1016	1.83885	14.4928	216.77	3739.28
70	4900	343000	8.3666	4.1213	1.84510	14.2857	219.91	3848.45
71	5041	357911	8.4261	4.1408	1.85126	14.0845	223.05	3959.19
72	5184	373248	8.4853	4.1602	1.85733	13.8889	226.19	4071.50
73	5329	389017	8.5440	4.1793	1.86332	13.6986	229.34	4185.39
74	5476	405224	8.6023	4.1983	1.86923	13.5135	232.48	4300.84
75	5625	421875	8.6603	4.2172	1.87506	13.3333	235.62	4417.86
76	5776	438976	8.7178	4.2358	1.88081	13.1579	238.76	4536.46
77	5929	456533	8.7750	4.2543	1.88649	12.9870	241.90	4656.63
78	6084	474552	8.8318	4.2727	1.89209	12.8205	245.04	4778.36
79	6241	493039	8.8882	4.2908	1.89763	12.6582	248.19	4901.67
80	6400	512000	8.9443	4.3089	1.90309	12.5000	251.33	5026.55
81	6561	531441	9.0000	4.3267	1.90849	12.3457	254.47	5153.00
82	6724	551368	9.0554	4.3445	1.91381	12.1951	257.61	5281.02
83	6889	571787	9.1104	4.3621	1.91908	12.0482	260.75	5410.61
84	7056	592704	9.1652	4.3795	1.92428	11.9048	263.89	5541.77
85	7225	614125	9.2195	4.3968	1.92942	11.7647	267.04	5674.50
86	7396	636056	9.2736	4.4140	1.93450	11.6279	270.18	5808.80
87	7569	658503	9.3274	4.4310	1.93952	11.4943	273.32	5944.68
88	7744	681472	9.3808	4.4480	1.94448	11.3636	276.46	6082.12
89	7921	704969	9.4340	4.4647	1.94939	11.2360	279.60	6221.14
90	8100	729000	9.4868	4.4814	1.95424	11.1111	282.74	6361.73
91	8281	753571	9.5394	4.4979	1.95904	10.9890	285.88	6503.88
92	8464	778688	9.5917	4.5144	1.96379	10.8696	289.03	6647.61
93	8649	804357	9.6437	4.5307	1.96848	10.7527	292.17	6792.91
94	8836	830584	9.6954	4.5468	1.97313	10.6383	295.31	6939.78
95	9025	857375	9.7468	4.5629	1.97772	10.5263	298.45	7088.22
96	9216	884736	9.7980	4.5789	1.98227	10.4167	301.59	7238.23
97	9409	912673	9.8489	4.5947	1.98677	10.3093	304.73	7389.81
98	9604	941192	9.8995	4.6104	1.99123	10.2041	307.88	7542.96
99	9801	970299	9.9499	4.6261	1.99564	10.1010	311.02	7697.69

FUNCTIONS OF NUMBERS

No.	Square	Cube	Square Root	Cube Root	Logarithm	1000 × Reciprocal	No. = Diameter	
							Circum.	Area
100	10000	1000000	10.0000	4.6416	2.00000	10.0000	314.16	7853.98
101	10201	1030301	10.0499	4.6570	2.00432	9.90099	317.30	8011.85
102	10404	1061208	10.0995	4.6723	2.00860	9.80392	320.44	8171.28
103	10609	1092727	10.1489	4.6875	2.01284	9.70874	323.58	8332.29
104	10816	1124864	10.1980	4.7027	2.01703	9.61538	326.73	8494.87
105	11025	1157625	10.2470	4.7177	2.02119	9.52381	329.87	8659.01
106	11236	1191016	10.2956	4.7326	2.02531	9.43396	333.01	8824.73
107	11449	1225043	10.3441	4.7475	2.02938	9.34579	336.15	8992.02
108	11664	1259712	10.3923	4.7622	2.03342	9.25926	339.29	9160.88
109	11881	1295029	10.4403	4.7769	2.03743	9.17431	342.43	9331.32
110	12100	1331000	10.4881	4.7914	2.04139	9.09091	345.58	9503.32
111	12321	1367631	10.5357	4.8059	2.04532	9.00901	348.72	9676.89
112	12544	1404928	10.5830	4.8203	2.04922	8.92857	351.86	9852.03
113	12769	1442897	10.6301	4.8346	2.05308	8.84956	355.00	10028.7
114	12996	1481544	10.6771	4.8488	2.05690	8.77193	358.14	10207.0
115	13225	1520875	10.7238	4.8629	2.06070	8.69565	361.28	10386.9
116	13456	1560896	10.7703	4.8770	2.06446	8.62069	364.42	10568.3
117	13689	1601613	10.8167	4.8910	2.06819	8.54701	367.57	10751.3
118	13924	1643032	10.8628	4.9049	2.07188	8.47458	370.71	10935.9
119	14161	1685159	10.9087	4.9187	2.07555	8.40336	373.85	11122.0
120	14400	1728000	10.9545	4.9324	2.07918	8.33333	376.99	11309.7
121	14641	1771561	11.0000	4.9461	2.08279	8.26446	380.13	11499.0
122	14884	1815848	11.0454	4.9597	2.08636	8.19672	383.27	11689.9
123	15129	1860867	11.0905	4.9732	2.08991	8.13008	386.42	11882.3
124	15376	1906624	11.1355	4.9866	2.09342	8.06452	389.56	12076.3
125	15625	1953125	11.1803	5.0000	2.09691	8.00000	392.70	12271.8
126	15876	2000376	11.2250	5.0133	2.10037	7.93651	395.84	12469.0
127	16129	2048383	11.2694	5.0265	2.10380	7.87402	398.98	12667.7
128	16384	2097152	11.3137	5.0397	2.10721	7.81250	402.12	12868.0
129	16641	2146689	11.3578	5.0528	2.11059	7.75194	405.27	13069.8
130	16900	2197000	11.4018	5.0658	2.11394	7.69231	408.41	13273.2
131	17161	2248091	11.4455	5.0788	2.11727	7.63359	411.55	13478.2
132	17424	2299968	11.4891	5.0916	2.12057	7.57576	414.69	13684.8
133	17689	2352637	11.5326	5.1045	2.12385	7.51880	417.83	13892.9
134	17956	2406104	11.5758	5.1172	2.12710	7.46269	420.97	14102.6
135	18225	2460375	11.6190	5.1299	2.13033	7.40741	424.12	14313.9
136	18496	2515456	11.6619	5.1426	2.13354	7.35294	427.26	14526.7
137	18769	2571353	11.7047	5.1551	2.13672	7.29927	430.40	14741.1
138	19044	2628072	11.7473	5.1676	2.13988	7.24638	433.54	14957.1
139	19321	2685619	11.7898	5.1801	2.14301	7.19424	436.68	15174.7
140	19600	2744000	11.8322	5.1925	2.14613	7.14286	439.82	15393.8
141	19881	2803221	11.8743	5.2048	2.14922	7.09220	442.96	15614.5
142	20164	2863288	11.9164	5.2171	2.15229	7.04225	446.11	15836.8
143	20449	2924207	11.9583	5.2293	2.15534	6.99301	449.25	16060.6
144	20736	2985984	12,0000	5.2415	2.15836	6.94444	452.39	16286.0
145	21025	3048625	12.0416	5.2536	2.16137	6.89655	455.53	16513.0
146	21316	3112136	12.0830	5.2656	2.16435	6.84932	458.67	16741.5
147	21609	3176523	12.1244	5.2776	2.16732	6.80272	461.81	16971.7
148	21904	3241792	12.1655	5.2896	2.17026	6.75676	464.96	17203.4
149	22201	3307949	12.2066	5.3015	2.17319	6.71141	468.10	17436.6

FUNCTIONS OF NUMBERS

No.	Square	Cube	Square Root	Cube Root	Logarithm	1000 × Reciprocal	No. = Diameter	
							Circum.	Area
150	22500	3375000	12.2474	5.3133	2.17609	6.66667	471.24	17671.5
151	22801	3442951	12.2882	5.3251	2.17898	6.62252	474.38	17907.9
152	23104	3511808	12.3288	5.3368	2.18184	6.57895	477.52	18145.8
153	23409	3581577	12.3693	5.3485	2.18469	6.53595	480.66	18385.4
154	23716	3652264	12.4097	5.3601	2.18752	6.49351	483.81	18626.5
155	24025	3723875	12.4499	5.3717	2.19033	6.45161	486.95	18869.2
156	24336	3796416	12.4900	5.3832	2.19312	6.41026	490.09	19113.4
157	24649	3869893	12.5300	5.3947	2.19590	6.36943	493.23	19359.3
158	24964	3944312	12.5698	5.4061	2.19866	6.32911	496.37	19606.7
159	25281	4019679	12.6095	5.4175	2.20140	6.28931	499.51	19855.7
160	25600	4096000	12.6491	5.4288	2.20412	6.25000	502.65	20106.2
161	25921	4173281	12.6886	5.4401	2.20683	6.21118	505.80	20358.3
162	26244	4251528	12.7279	5.4514	2.20952	6.17284	508.94	20612.0
163	26569	4330747	12.7671	5.4626	2.21219	6.13497	512.08	20867.2
164	26896	4410944	12.8062	5.4737	2.2148	6.09756	515.22	21124.1
165	27225	4492125	12.8452	5.4848	2.21748	6.06061	518.36	21382.5
166	27556	4574296	12.8841	5.4959	2.22011	6.02410	521.50	21642.4
167	27889	4657463	12.9228	5.5069	2.22272	5.98802	524.65	21904.0
168	28224	4741632	12.9615	5.5178	2.22531	5.95238	527.79	22167.1
169	28561	4826809	13.0000	5.5288	2.22789	5.91716	530.93	22431.8
170	28900	4913000	13.0384	5.5397	2.23045	5.88235	534.07	22698.0
171	29241	5000211	13.0767	5.5505	2.23300	5.84795	537.21	22965.8
172	29584	5088448	13.1149	5.5613	2.23553	5.81395	540.35	23235.2
173	29929	5177717	13.1529	5.5721	2.23805	5.78035	543.50	23506.2
174	30276	5268024	13.1909	5.5828	2.24055	5.74713	546.64	23778.7
175	30625	5359375	13.2288	5.5934	2.24304	5.71429	549.78	24052.8
176	30976	5451776	13.2665	5.6041	2.24551	5.68182	552.92	24328.5
177	31329	5545233	13.3041	5.6147	2.24797	5.64972	556.06	24605.7
178	31684	5639752	13.3417	5.6252	2.25042	5.61798	559.20	24884.6
179	32041	5735339	13.3791	5.6357	2.25285	5.58659	562.35	25164.9
180	32400	5832000	13.4164	5.6462	2.25527	5.55556	565.49	25446.9
181	32761	5929741	13.4536	5.6567	2.25768	5.52486	568.63	25730.4
182	33124	6028568	13.4907	5.6671	2.26007	5.49451	571.77	26015.5
183.	33489	6128487	13.5277	5.6774	2.26245	5.46448	574.91	26302.2
184	33856	6229504	13.5647	5.6877	2.26482	5.43478	578.05	26590.4
185	34225	6331625	13.6015	5.6980	2.26717	5.40541	581.19	26880.3
186	34596	6434856	13.6382	5.7083	2.26951	5.37634	584.34	27171.6
187	34969	6539203	13.6748	5.7185	2.27184	5.34759	587.48	27464.6
188	35344	6644672	13.7113	5.7287	2.27416	5.31915	590.62	27759.1
189	35721	6751269	13.7477	5.7388	2.27646	5.29101	593.76	28055.2
190	36100	6859000	13.7840	5.7489	2.27875	5.26316	596.90	28352.9
191	36481	6967871	13.8203	5.7590	2.28103	5.23560	600.04	28652.1
192	36864	7077888	13.8564	5.7690	2.28330	5.20833	603.19	28952.9
193	37249	7189057	13.8924	5.7790	2.28556	5.18135	606.33	29255.3
194	37636	7301384	13.9284	5.7890	2.28780	5.15464	609.47	29559.2
195	38025	7414875	13.9642	5.7989	2.29003	5.12821	612.61	29864.8
196	38416	7529536	14.0000	5.8088	2.29226	5.10204	615.75	30171.9
197	38809	7645373	14.0357	5.8186	2.29447	5.07614	618.89	30480.5
198	39204	7762392	14.0712	5.8285	2.29667	5.05051	622.04	30790.7
199	39601	7880599	14.1067	5.8383	2.29885	5.02513	625.18	31102.6

FUNCTIONS OF NUMBERS

No.	Square	Cube	Square Root	Cube Root	Logarithm	1000 × Reciprocal	No. = Diameter	
							Circum.	Area
200	40000	8000000	14.1421	5.8480	2.30103	5.00000	628.32	31415.9
201	40401	8120601	14.1774	5.8578	2.30320	4.97512	631.46	31730.9
202	40804	8242408	14.2127	5.8675	2.30535	4.95050	634.60	32047.4
203	41209	8365427	14.2478	5.8771	2.30750	4.92611	637.74	32365.5
204	41616	8489664	14.2829	5.8868	2.30963	4.90196	640.88	32685.1
205	42025	8615125	14.3178	5.8964	2.31175	4.87805	644.03	33006.4
206	42436	8741816	14.3527	5.9059	2.31387	4.85437	647.17	33329.2
207	42849	8869743	14.3875	5.9155	2.31597	4.83092	650.31	33653.5
208	43264	8998912	14.4222	5.9250	2.31806	4.80769	653.45	33979.5
209	43681	9129329	14.4568	5.9345	2.32015	4.78469	656.59	34307.0
210	44100	9261000	14.4914	5.9439	2.32222	4.76190	659.73	34636.1
211	44521	9393931	14.5258	5.9533	2.32428	4.73934	662.88	34966.7
212	44944	9528128	14.5602	5.9627	2.32634	4.71698	666.02	35298.9
213	45369	9663597	14.5945	5.9721	2.32838	4.69484	669.16	35632.7
214	45796	9800344	14.6287	5.9814	2.33041	4.67290	672.30	35968.1
215	46225	9938375	14.6629	5.9907	2.33244	4.65116	675.44	36305.0
216	46656	10077696	14.6969	6.0000	2.33445	4.62963	678.58	36643.5
217	47089	10218313	14.7309	6.0092	2.33646	4.60829	681.73	36983.6
218	47524	10360232	14.7648	6.0185	2.33846	4.58716	684.87	37325.3
219	47961	10503459	14.7986	6.0277	2.34044	4.56621	688.01	37668.5
220	48400	10648000	14.8324	6.0368	2.34242	4.54545	691.15	38013.3
221	48841	10793861	14.8661	6.0459	2.34439	4.52489	694.29	38359.6
222	49284	10941048	14.8997	6.0550	2.34635	4.50450	697.43	38707.6
223	49729	11089567	14.9332	6.0641	2.34830	4.48430	700.58	39057.1
224	50176	11239424	14.9666	6.0732	2.35025	4.46429	703.72	39408.1
225	50625	11390625	15.0000	6.0822	2.35218	4.44444	706.86	39760.8
226	51076	11543176	15.0333	6.0912	2.35411	4.42478	710.00	40115.0
227	51529	11697083	15.0665	6.1002	2.35603	4.40529	713.14	40470.8
228	51984	11852352	15.0997	6.1091	2.35793	4.38596	716.28	40828.1
229	52441	12008989	15.1327	6.1180	2.35984	4.36681	719.42	41187.1
230	52900	12167000	15.1658	6.1269	2.36173	4.34783	722.57	41547.6
231	53361	12326391	15.1987	6.1358	2.36361	4.32900	725.71	41909.6
232	53824	12487168	15.2315	6.1446	2.36549	4.31034	728.85	42273.3
233	54289	12649337	15.2643	6.1534	2.36736	4.29185	731.99	42638.5
234	54756	12812904	15.2971	6.1622	2.36922	4.27350	735.13	43005.3
235	55225	12977875	15.3297	6.1710	2.37107	4.25532	738.27	43373.6
236	55696	13144256	15.3623	6.1797	2.37291	4.23729	741.42	43743.5
237	56169	13312053	15.3948	6.1885	2.37475	4.21941	744.56	44115.0
238	56644	13481272	15.4272	6.1972	2.37658	4.20168	747.70	44488.1
239	57121	13651919	15.4596	6.2058	2.37840	4.18410	750.84	44862.7
240	57600	13824000	15.4919	6.2145	2.38021	4.16667	753.98	45238.9
241	58081	13997521	15.5242	6.2231	2.38202	4.14938	757.12	45616.7
242	58564	14172488	15.5563	6.2317	2.38382	4.13223	760.27	45996.1
243	59049	14348907	15.5885	6.2403	2.38561	4.11523	763.41	46377.0
244	59536	14526784	15.6205	6.2488	2.38739	4.09836	766.55	46759.5
245	60025	14706125	15.6525	6.2573	2.38917	4.08163	769.69	47143.5
246	60516	14886936	15.6844	6.2658	2.39094	4.06504	772.83	47529.2
247	61009	15069223	15.7162	6.2743	2.39270	4.04858	775.97	47916.4
248	61504	15252992	15.7480	6.2828	2.39445	4.03226	779.12	48305.1
249	62001	15438249	15.7797	6.2912	2.39620	4.01606	782.26	48695.5

FUNCTIONS OF NUMBERS

No.	Square	Cube	Square Root	Cube Root	Logarithm	1000 × Reciprocal	No. = Diameter	
							Circum.	Area
250	62500	15625000	15.8114	6.2996	2.39794	4.00000	785.40	49087.4
251	63001	15813251	15.8430	6.3080	2.39967	3.98406	788.54	49480.9
252	63504	16003008	15.8745	6.3164	2.40140	3.96825	791.68	49875.9
253	64009	16194277	15.9060	6.3247	2.40312	3.95257	794.82	50272.6
254	64516	16387064	15.9374	6.3330	2.40483	3.93701	797.96	50670.7
255	65025	16581375	15.9687	6.3413	2.40654	3.92157	801.11	51070.5
256	65536	16777216	16.0000	6.3496	2.40824	3.90625	804.25	51471.9
257	66049	16974593	16.0312	6.3579	2.40993	3.89105	807.39	51874.8
258	66564	17173512	16.0624	6.3661	2.41162	3.87597	810.53	52279.2
259	67081	17373979	16.0935	6.3743	2.41330	3.86100	813.67	52685.3
260	67600	17576000	16.1245	6.3825	2.41497	3.84615	816.81	53092.9
261	68121	17779581	16.1555	6.3907	2.41664	3.83142	819.96	53502.1
262	68644	17984728	16.1864	6.3988	2.41830	3.81679	823.10	53912.9
263	69169	18191447	16.2173	6.4070	2.41996	3.80228	826.24	54325.2
264	69696	18399744	16.2481	6.4151	2.42160	3.78788	829.38	54739.1
265	70225	18609625	16.2788	6.4232	2.42325	3.77358	832.52	55154.6
266	70756	18821096	16.3095	6.4312	2.42488	3.75940	835.66	55571.6
267	71289	19034163	16.3401	6.4393	2.42651	3.74532	838.81	55990.2
268	71824	19248832	16.3707	6.4473	2.42813	3.73134	841.95	56410.4
269	72361	19465109	16.4012	6.4553	2.42975	3.71747	845.09	56832.2
270	72900	19683000	16.4317	6.4633	2.43136	3.70370	848.23	57255.5
271	73441	19902511	16.4621	6.4713	2.43297	3.69004	851.37	57680.4
272	73984	20123648	16.4924	6.4792	2.43457	3.67647	854.51	58106.9
273	74529	20346417	16.5227	6.4872	2.43616	3.66300	857.65	58534.9
274	75076	20570824	16.5529	6.4951	2.43775	3.64964	860.80	58964.6
275	75625	20796875	16.5831	6.5030	2.43933	3.63636	863.94	59395.7
276	76176	21024576	16.6132	6.5108	2.44091	3.62319	867.08	59828.5
277	76729	21253933	16.6433	6.5187	2.44248	3.61011	870.22	60262.8
278	77284	21484952	16.6733	6.5265	2.44404	3.59712	873.36	60698.7
279	77841	21717639	16.7033	6.5343	2.44560	3.58423	876.50	61136.2
280	78400	21952000	16.7332	6.5421	2.44716	3.57143	879.65	61575.2
281	78961	22188041	16.7631	6.5499	2.44871	3.55872	882.79	62015.8
282	79524	22425768	16.7929	6.5577	2.45025	3.54610	885.93	62458.0
283	80089	22665187	16.8226	6.5654	2.45179	3.53357	889.07	62901.8
284	80656	22906304	16.8523	6.5731	2.45332	3.52113	892.21	63347.1
285	81225	23149125	16.8819	6.5808	2.45484	3.50877	895.35	63794.0
286	81796	23393656	16.9115	6.5885	2.45637	3.49650	898.50	64242.4
287	82369	23639903	16.9411	6.5962	2.45788	3.48432	901.64	64692.5
288	82944	23887872	16.9706	6.6039	2.45939	3.47222	904.78	65144.1
289	83521	24137569	17.0000	6.6115	2.46090	3.46021	907.92	65597.2
290	84100	24389000	17.0294	6.6191	2.46240	3.44828	911.06	66052.0
291	84681	24642171	17.0587	6.6267	2.46389	3.43643	914.20	66508.3
292	85264	24897088	17.0880	6.6343	2.46538	3.42466	917.35	66966.2
293	85849	25153757	17.1172	6.6419	2.46687	3.41297	920.49	67425.6
294	86436	25412184	17.1464	6.6494	2.46835	3.40136	923.63	67886.7
295	87025	25672375	17.1756	6.6569	2.46982	3.38983	926.77	68349.3
296	87616	25934336	17.2047	6.6644	2.47129	3.37838	929.91	68813.4
297	88209	26198073	17.2337	6.6719	2.47276	3.36700	933.05	69279.2
298	88804	26463592	17.2627	6.6794	2.47422	3.35570	936.19	69746.5
299	89401	26730899	17.2916	6.6869	2.47567	3.34448	939.34	70215.4

FUNCTIONS OF NUMBERS

No.	Square	Cube	Square Root	Cube Root	Logarithm	1000 × Reciprocal	No. = Diameter	
							Circum.	Area
300	90000	27000000	17.3205	6.6943	2.47712	3.33333	942.48	70685.8
301	90601	27270901	17.3494	6.7018	2.47857	3.32226	945.62	71157.9
302	91204	27543608	17.3781	6.7092	2.48001	3.31126	948.76	71631.5
303	91809	27818127	17.4069	6.7166	2.48144	3.30033	951.90	72106.6
304	92416	28094464	17.4356	6.7240	2.48287	3.28947	955.04	72583.4
305	93025	28372625	17.4642	6.7313	2.48430	3.27869	958.19	73061.7
306	93636	28652616	17.4929	6.7387	2.48572	3.26797	961.33	73541.5
307	94249	28934443	17.5214	6.7460	2.48714	3.25733	964.47	74023.0
308	94864	29218112	17.5499	6.7533	2.48855	3.24675	967.61	74506.0
309	95481	29503629	17.5784	6.7606	2.48996	3.23625	970.75	74990.6
310	96100	29791000	17.6068	6.7679	2.49136	3.22581	973.89	75476.8
311	96721	30080231	17.6352	6.7752	2.49276	3.21543	977.04	75964.5
312	97344	30371328	17.6635	6.7824	2.49415	3.20513	980.18	76453.8
313	97969	30664297	17.6918	6.7897	2.49554	3.19489	983.32	76944.7
314	98596	30959144	17.7200	6.7969	2.49693	3.18471	986.46	77437.1
315	99225	31255875	17.7482	6.8041	2.49831	3.17460	989.60	77931.1
316	99856	31554496	17.7764	6.8113	2.49969	3.16456	992.74	78426.7
317	100489	31855013	17.8045	6.8185	2.50106	3.15457	995.88	78923.9
318	101124	32157432	17.8326	6.8256	2.50243	3.14465	999.03	79422.6
319	101761	32461759	17.8606	6.8328	2.50379	3.13480	1002.2	79922.9
320	102400	32768000	17.8885	6.8399	2.50515	3.12500	1005.3	80424.8
321	103041	33076161	17.9165	6.8470	2.50651	3.11526	1008.5	80928.2
322	103684	33386248	17.9444	6.8541	2.50786	3.10559	1011.6	81433.2
323	104329	33698267	17.9722	6.8612	2.50920	3.09598	1014.7	81939.8
324	104976	34012224	18.0000	6.8683	2.51055	3.08642	1017.9	82448.0
325	105625	34328125	18.0278	6.8753	2.51188	3.07692	1021.0	82957.7
326	106276	34645976	18.0555	6.8824	2.51322	3.06749	1024.2	83469.0
327	106929	34965783	18.0831	6.8894	2.51455	3.05810	1027.3	83981.8
328	107584	35287552	18.1108	6.8964	2.51587	3.04878	1030.4	84496.3
329	108241	35611289	18.1384	6.9034	2.51720	3.03951	1033.6	85012.3
330	108900	35937000	18.1659	6.9104	2.51851	3.03030	1036.7	85529.9
331	109561	36264691	18.1934	6.9174	2.51983	3.02115	1039.9	86049.0
332	110224	36594368	18.2209	6.9244	2.52114	3.01205	1043.0	86569.7
333	110889	36926037	18.2483	6.9313	2.52244	3.00300	1046.2	87092.0
334	111556	37259704	18.2757	6.9382	2.52375	2.99401	1049.3	87615.9
335	112225	37595375	18.3030	6.9451	2.52504	2.98507	1052.4	88141.3
336	112896	37933056	18.3303	6.9521	2.52634	2.97619	1055.6	88668.3
337	113569	38272753	18.3576	6.9589	2.52763	2.96736	1058.7	89196.9
338	114244	38614472	18.3848	6.9658	2.52892	2.95858	1061.9	89727.0
339	114921	38958219	18.4120	6.9727	2.53020	2.94985	1065.0	90258.7
340	115600	39304000	18.4391	6.9795	2.53148	2.94118	1068.1	90792.0
341	116281	39651821	18.4662	6.9864	2.53275	2.93255	1071.3	91326.9
342	116964	40001688	18.4932	6.9932	2.53403	2.92398	1074.4	91863.3
343	117649	40353607	18.5203	7.0000	2.53529	2.91545	1077.6	92401.3
344	118336	40707584	18.5472	7.0068	2.53656	2.90698	1080.7	92940.9
345	119025	41063625	18.5742	7.0136	2.53782	2.89855	1083.8	93482.0
346	119716	41421736	18.6011	7.0203	2.53908	2.89017	1087.0	94024.7
347	120409	41781923	18.6279	7.0271	2.54033	2.88184	1090.1	94569.0
348	121104	42144192	18.6548	7.0338	2.54158	2.87356	1093.3	95114.9
349	121801	42508549	18.6815	7.0406	2.54283	2.86533	1096.4	95662.3

FUNCTIONS OF NUMBERS

No.	Square	Cube	Square Root	Cube Root	Logarithm	1000 × Reciprocal	No. = Circum.	No. = Area
350	122500	42875000	18.7083	7.0473	2.54407	2.85714	1099.6	96211.3
351	123201	43243551	18.7350	7.0540	2.54531	2.84900	1102.7	96761.8
352	123904	43614208	18.7617	7.0607	2.54654	2.84091	1105.8	97314.0
353	124609	43986977	18.7883	7.0674	2.54777	2.83286	1109.0	97867.7
354	125316	44361864	18.8149	7.0740	2.54900	2.82486	1112.1	98423.0
355	126025	44738875	18.8414	7.0807	2.55023	2.81690	1115.3	98979.8
356	126736	45118016	18.8680	7.0873	2.55145	2.80899	1118.4	99538.2
357	127449	45499293	18.8944	7.0940	2.55267	2.80112	1121.5	100098
358	128164	45882712	18.9209	7.1006	2.55388	2.79330	1124.7	100660
359	128881	46268279	18.9473	7.1072	2.55509	2.78552	1127.8	101223
360	129600	46656000	18.9737	7.1138	2.55630	2.77778	1131.0	101788
361	130321	47045881	19.0000	7.1204	2.55751	2.77008	1134.1	102354
362	131044	47437928	19.0263	7.1269	2.55871	2.76243	1137.3	102922
363	131769	47832147	19.0526	7.1335	2.55991	2.75482	1140.4	103491
364	132496	48228544	19.0788	7.1400	2.56110	2.74725	1143.5	104062
365	133225	48627125	19.1050	7.1466	2.56229	2.73973	1146.7	104635
366	133956	49027896	19.1311	7.1531	2.56348	2.73224	1149.8	105209
367	134689	49430863	19.1572	7.1596	2.56467	2.72480	1153.0	105785
368	135424	49836032	19.1833	7.1661	2.56585	2.71739	1156.1	106362
369	136161	50243409	19.2094	7.1726	2.56703	2.71003	1159.2	106941
370	136900	50653000	19.2354	7.1791	2.56820	2.70270	1162.4	107521
371	137641	51064811	19.2614	7.1855	2.56937	2.69542	1165.5	108103
372	138384	51478848	19.2873	7.1920	2.57054	2.68817	1168.7	108687
373	139129	51895117	19.3132	7.1984	2.57171	2.68097	1171.8	109272
374	139876	52313624	19.3391	7.2048	2.57287	2.67380	1175.0	109858
375	140625	52734375	19.3649	7.2112	2.57403	2.66667	1178.1	110447
376	141376	53157376	19.3907	7.2177	2.57519	2.65957	1181.2	111036
377	142129	53582633	19.4165	7.2240	2.57634	2.65252	1184.4	111628
378	142884	54010152	19.4422	7.2304	2.57749	2.64550	1187.5	112221
379	143641	54439939	19.4679	7.2368	2.57864	2.63852	1190.7	112815
380	144400	54872000	19.4936	7.2432	2.57978	2.63158	1193.8	113411
381	145161	55306341	19.5192	7.2495	2.58093	2.62467	1196.9	114009
382	145924	55742968	19.5448	7.2558	2.58206	2.61780	1200.1	114608
383	146689	56181887	19.5704	7.2622	2.58320	2.61097	1203.2	115209
384	147456	56623104	19.5959	7.2685	2.58433	2.60417	1206.4	115812
385	148225	57066625	19.6214	7.2748	2.58546	2.59740	1209.5	116416
386	148996	57512456	19.6469	7.2811	2.58659	2.59067	1212.7	117021
387	149769	57960603	19.6723	7.2874	2.58771	2.58398	1215.8	117628
388	150544	58411072	19.6977	7.2936	2.58883	2.57732	1218.9	118237
389	151321	58863869	19.7231	7.2999	2.58995	2.57069	1222.1	118847
390	152100	59319000	19.7484	7.3061	2.59106	2.56410	1225.2	119459
391	152881	59776471	19.7737	7.3124	2.59218	2.55754	1228.4	120072
392	153664	60236288	19.7990	7.3186	2.59329	2.55102	1231.5	120687
393	154449	60698457	19.8242	7.3248	2.59439	2.54453	1234.6	121304
394	155236	61162984	19.8494	7.3310	2.59550	2.53807	1237.8	121922
395	156025	61629875	19.8746	7.3372	2.59660	2.53165	1240.9	122542
396	156816	62099136	19.8997	7.3434	2.59770	2.52525	1244.1	123163
397	157609	62570773	19.9249	7.3496	2.59879	2.51889	1247.2	123786
398	158404	63044792	19.9499	7.3558	2.59988	2.51256	1250.4	124410
399	159201	63521199	19.9750	7.3619	2.60097	2.50627	1253.5	125036

FUNCTIONS OF NUMBERS

No.	Square	Cube	Square Root	Cube Root	Logarithm	1000 × Reciprocal	No. = Diameter	
							Circum.	Area
400	160000	64000000	20.0000	7.3681	2.60206	2.50000	1256.6	125664
401	160801	64481201	20.0250	7.3742	2.60314	2.49377	1259.8	126293
402	161604	64964808	20.0499	7.3803	2.60423	2.48756	1262.9	126923
403	162409	65450827	20.0749	7.3864	2.60531	2.48139	1266.1	127556
404	163216	65939264	20.0998	7.3925	2.60638	2.47525	1269.2	128190
405	164025	66430125	20.1246	7.3986	2.60746	2.46914	1272.3	128825
406	164836	66923416	20.1494	7.4047	2.60853	2.46305	1275.5	129462
407	165649	67419143	20.1742	7.4108	2.60959	2.45700	1278.6	130100
408	166464	67917312	20.1990	7.4169	2.61066	2.45098	1281.8	130741
409	167281	68417929	20.2237	7.4229	2.61172	2.44499	1284.9	131382
410	168100	68921000	20.2485	7.4290	2.61278	2.43902	1288.1	132025
411	168921	69426531	20.2731	7.4350	2.61384	2.43309	1291.2	132670
412	169744	69934528	20.2978	7.4410	2.61490	2.42718	1294.3	133317
413	170569	70444997	20.3224	7.4470	2.61595	2.42131	1297.5	133965
414	171396	70957944	20.3470	7.4530	2.61700	2.41546	1300.6	134614
415	172225	71473375	20.3715	7.4590	2.61805	2.40964	1303.8	135265
416	173056	71991296	20.3961	7.4650	2.61909	2.40385	1306.9	135918
417	173889	72511713	20.4206	7.4710	2.62014	2.39808	1310.0	136572
418	174724	73034632	20.4450	7.4770	2.62118	2.39234	1313.2	137228
419	175561	73560059	20.4695	7.4829	2.62221	2.38663	1316.3	137885
420	176400	74088000	20.4939	7.4889	2.62325	2.38095	1319.5	138544
421	177241	74618461	20.5183	7.4948	2.62428	2.37530	1322.6	139205
422	178084	75151448	20.5426	7.5007	2.62531	2.36967	1325.8	139867
423	178929	75686967	20.5670	7.5067	2.62634	2.36407	1328.9	140531
424	179776	76225024	20.5913	7.5126	2.62737	2.35849	1332.0	141196
425	180625	76765625	20.6155	7.5185	2.62839	2.35294	1335.2	141863
426	181476	77308776	20.6398	7.5244	2.62941	2.34742	1338.3	142531
427	182329	77854483	20.6640	7.5302	2.63043	2.34192	1341.5	143201
428	183184	78402752	20.6882	7.5361	2.63144	2.33645	1344.6	143872
429	184041	78953589	20.7123	7.5420	2.63246	2.33100	1347.7	144545
430	184900	79507000	20.7364	7.5478	2.63347	2.32558	1350.9	145220
431	185761	80062991	20.7605	7.5537	2.63448	2.32019	1354.0	145896
432	186624	80621568	20.7846	7.5595	2.63548	2.31481	1357.2	146574
433	187489	81182737	20.8087	7.5654	2.63649	2.30947	1360.3	147254
434	188356	81746504	20.8327	7.5712	2.63749	2.30415	1363.5	147934
435	189225	82312875	20.8567	7.5770	2.63849	2.29885	1366.6	148617
436	190096	82881856	20.8806	7.5828	2.63949	2.29358	1369.7	149301
437	190969	83453453	20.9045	7.5886	2.64048	2.28833	1372.9	149987
438	191844	84027672	20.9284	7.5944	2.64147	2.28311	1376.0	150674
439	192721	84604519	20.9523	7.6001	2.64246	2.27790	1379.2	151363
440	193600	85184000	20.9762	7.6059	2.64345	2.27273	1382.3	152053
441	194481	85766121	21.0000	7.6117	2.64444	2.26757	1385.4	152745
442	195364	86350888	21.0238	7.6174	2.64542	2.26244	1388.6	153439
443	196249	86938307	21.0476	7.6232	2.64640	2.25734	1391.7	154134
444	197136	87528384	21.0713	7.6289	2.64738	2.25225	1394.9	154830
445	198025	88121125	21.0950	7.6346	2.64836	2.24719	1398.0	155528
446	198916	88716536	21.1187	7.6403	2.64933	2.24215	1401.2	156228
447	199809	89314623	21.1424	7.6460	2.65031	2.23714	1404.3	156930
448	200704	89915392	21.1660	7.6517	2.65128	2.23214	1407.4	157633
449	201601	90518849	21.1896	7.6574	2.65225	2.22717	1410.6	158337

FUNCTIONS OF NUMBERS

No.	Square	Cube	Square Root	Cube Root	Logarithm	1000 × Reciprocal	No. = Diameter	
							Circum.	Area
450	202500	91125000	21.2132	7.6631	2.65321	2.22222	1413.7	159043
451	203401	91733851	21.2368	7.6688	2.65418	2.21729	1416.9	159751
452	204304	92345408	21.2603	7.6744	2.65514	2.21239	1420.0	160460
453	205209	92959677	21.2838	7.6801	2.65610	2.20751	1423.1	161171
454	206116	93576664	21.3073	7.6857	2.65706	2.20264	1426.3	161883
455	207025	94196375	21.3307	7.6914	2.65801	2.19780	1429.4	162597
456	207936	94818816	21.3542	7.6970	2.65896	2.19298	1432.6	163313
457	208849	95443993	21.3776	7.7026	2.65992	2.18818	1435.7	164030
458	209764	96071912	21.4009	7.7082	2.66087	2.18341	1438.8	164748
459	210681	96702579	21.4243	7.7138	2.66181	2.17865	1442.0	165468
460	211600	97336000	21.4476	7.7194	2.66276	2.17391	1445.1	166190
461	212521	97972181	21.4709	7.7250	2.66370	2.16920	1448.3	166914
462	213444	98611128	21.4942	7.7306	2.66464	2.16450	1451.4	167639
463	214369	99252847	21.5174	7.7362	2.66558	2.15983	1454.6	168365
464	215296	99897344	21.5407	7.7418	2.66652	2.15517	1457.7	169093
465	216225	100544625	21.5639	7.7473	2.66745	2.15054	1460.8	169823
466	217156	101194696	21.5870	7.7529	2.66839	2.14592	1464.0	170554
467	218089	101847563	21.6102	7.7584	2.66932	2.14133	1467.1	171287
468	219024	102503232	21.6333	7.7639	2.67025	2.13675	1470.3	172021
469	219961	103161709	21.6564	7.7695	2.67117	2.13220	1473.4	172757
470	220900	103823000	21.6795	7.7750	2.67210	2.12766	1476.5	173494
471	221841	104487111	21.7025	7.7805	2.67302	2.12314	1479.7	174234
472	222784	105154048	21.7256	7.7860	2.67394	2.11864	1482.8	174974
473	223729	105823817	21.7486	7.7915	2.67486	2.11416	1496.0	175716
474	224676	106496424	21.7715	7.7970	2.67578	2.10970	1489.1	176460
475	225625	107171875	21.7945	7.8025	2.67669	2.10526	1492.3	177205
476	226576	107850176	21.8174	7.8079	2.67761	2.10084	1495.4	177952
477	227529	108531333	21.8403	7.8134	2.67852	2.09644	1498.5	178701
478	228484	109215352	21.8632	7.8188	2.67943	2.09205	1501.7	179451
479	229441	109902239	21.8861	7.8243	2.68034	2.08768	1504.8	180203
480	230400	110592000	21.9089	7.8297	2.68124	2.08333	1508.0	180956
481	231361	111284641	21.9317	7.8352	2.68215	2.07900	1511.1	181711
482	232324	111980168	21.9545	7.8406	2.68305	2.07469	1514.2	182467
483	233289	112678587	21.9773	7.8460	2.68395	2.07039	1517.4	183225
484	234256	113379904	22.0000	7.8514	2.68485	2.06612	1520.5	183984
485	235225	114084125	22.0227	7.8568	2.68574	2.06186	1523.7	184745
486	236196	114791256	22.0454	7.8622	2.68664	2.05761	1526.8	185508
487	237169	115501303	22.0681	7.8676	2.68753	2.05339	1530.0	186272
488	238144	116214272	22.0907	7.8730	2.68842	2.04918	1533.1	187038
489	239121	116930169	22.1133	7.8784	2.68931	2.04499	1536.2	187805
490	240100	117649000	22.1359	7.8837	2.69020	2.04082	1539.4	188574
491	241081	118370771	22.1585	7.8891	2.69108	2.03666	1542.5	189345
492	242064	119095488	22.1811	7.8944	2.69197	2.03252	1545.7	190117
493	243049	119823157	22.2036	7.8998	2.69285	2.02840	1548.8	190890
494	244036	120553784	22.2261	7.9051	2.69373	2.02429	1551.9	191665
495	245025	121287375	22.2486	7.9105	2.69461	2.02020	1555.1	192442
496	246016	122023936	22.2711	7.9158	2.69548	2.01613	1558.2	193221
497	247009	122763473	22.2935	7.9211	2.69636	2.01207	1561.4	194000
498	248004	123505992	22.3159	7.9264	2.69723	2.00803	1564.5	194782
499	249001	124251499	22.3383	7.9317	2.69810	2.00401	1567.7	195565

FUNCTIONS OF NUMBERS

No.	Square	Cube	Square Root	Cube Root	Logarithm	1000 × Reciprocal	No. = Diameter Circum.	No. = Diameter Area
500	250000	125000000	22.3607	7.9370	2.69897	2.00000	1570.8	196350
501	251001	125751501	22.3830	7.9423	2.69984	1.99601	1573.9	197136
502	252004	126506008	22.4054	7.9476	2.70070	1.99203	1577.1	197923
503	253009	127263527	22.4277	7.9528	2.70157	1.98807	1580.2	198713
504	254016	128024064	22.4499	7.9581	2.70243	1.98413	1583.4	199504
505	255025	128787625	22.4722	7.9634	2.70329	1.98020	1586.5	200296
506	256036	129554216	22.4944	7.9686	2.70415	1.97628	1589.6	201090
507	257049	130323843	22.5167	7.9739	2.70501	1.97239	1592.8	201886
508	258064	131096512	22.5389	7.9791	2.70586	1.96850	1595.9	202683
509	259081	131872229	22.5610	7.9843	2.70672	1.96464	1599.1	203482
510	260100	132651000	22.5832	7.9896	2.70757	1.96078	1602.2	204282
511	261121	133432831	22.6053	7.9948	2.70842	1.95695	1605.4	205084
512	262144	134217728	22.6274	8.0000	2.70927	1.95312	1608.5	205887
513	263169	135005697	22.6495	8.0052	2.71012	1.94932	1611.6	206692
514	264196	135796744	22.6716	8.0104	2.71096	1.94553	1614.8	207499
515	265225	136590875	22.6936	8.0156	2.71181	1.94175	1617.9	208307
516	266256	137388096	22.7156	8.0208	2.71265	1.93798	1621.1	209117
517	267289	138188413	22.7376	8.0260	2.71349	1.93424	1624.2	209928
518	268324	138991832	22.7596	8.0311	2.71433	1.93050	1627.3	210741
519	269361	139798359	22.7816	8.0363	2.71517	1.92678	1630.5	211556
520	270400	140608000	22.8035	8.0415	2.71600	1.92308	1633.6	212372
521	271441	141420761	22.8254	8.0466	2.71684	1.91939	1636.8	213189
522	272484	142236648	22.8473	8.0517	2.71767	1.91571	1639.9	214008
523	273529	143055667	22.8692	8.0569	2.71850	1.91205	1643.1	214829
524	274576	143877824	22.8910	8.0620	2.71933	1.90840	1646.2	215651
525	275625	144703125	22.9129	8.0671	2.72016	1.90476	1649.3	216475
526	276676	145531576	22.9347	8.0723	2.72099	1.90114	1652.5	217301
527	277729	146363183	22.9565	8.0774	2.72181	1.89753	1655.6	218128
528	278784	147197952	22.9783	8.0825	2.72263	1.89394	1658.8	218956
529	279841	148035889	23.0000	8.0876	2.72346	1.89036	1661.9	219787
530	280900	148877000	23.0217	8.0927	2.72428	1.88679	1665.0	220618
531	281961	149721291	23.0434	8.0978	2.72509	1.88324	1668.2	221452
532	283024	150568768	23.0651	8.1028	2.72591	1.87970	1671.3	222287
533	284089	151419437	23.0868	8.1079	2.72673	1.87617	1674.5	223123
534	285156	152273304	23.1084	8.1130	2.72754	1.87266	1677.6	223961
535	286225	153130375	23.1301	8.1180	2.72835	1.86916	1680.8	224801
536	287296	153990656	23.1517	8.1231	2.72916	1.86567	1683.9	225642
537	288369	154854153	23.1733	8.1281	2.72997	1.86220	1687.0	226484
538	289444	155720872	23.1948	8.1332	2.73078	1.85874	1690.2	227329
539	290521	156590819	23.2164	8.1382	2.73159	1.85529	1693.3	228175
540	291600	157464000	23.2379	8.1433	2.73239	1.85185	1696.5	229022
541	292681	158340421	23.2594	8.1483	2.73320	1.84843	1699.6	229871
542	293764	159220088	23.2809	8.1533	2.73400	1.84502	1702.7	230722
543	294849	160103007	23.3024	8.1583	2.73480	1.84162	1705.9	231574
544	295936	160989184	23.3238	8.1633	2.73560	1.83824	1709.0	232428
545	297025	161878625	23.3452	8.1683	2.73640	1.83486	1712.2	233283
546	298116	162771336	23.3666	8.1733	2.73719	1.83150	1715.3	234140
547	299209	163667323	23.3880	8.1783	2.73799	1.82815	1718.5	234998
548	300304	164566592	23.4094	8.1833	2.73878	1.82482	1721.6	235858
549	301401	165469149	23.4307	8.1882	2.73957	1.82149	1724.7	236720

FUNCTIONS OF NUMBERS

No.	Square	Cube	Square Root	Cube Root	Logarithm	1000 × Reciprocal	No. = Diameter	
							Circum.	Area
550	302500	166375000	23.4521	8.1932	2.74036	81818	1727.9	237583
551	303601	167284151	23.4734	8.1982	2.74115	81488	1731.0	238448
552	304704	168196608	23.4947	8.2031	2.74194	81159	1734.2	239314
553	305809	169112377	23.5160	8.2081	2.74273	80832	1737.3	240182
554	306916	170031464	23.5372	8.2130	2.74351	1.80505	1740.4	241051
555	308025	170953875	23.5584	8.2180	2.74429	.80180	1743.6	241922
556	309136	171879616	23.5797	8.2229	2.74507	.79856	1746.7	242795
557	310249	172808693	23.6008	8.2278	2.74586	.79533	1749.9	243669
558	311364	173741112	23.6220	8.2327	2.74663	.79211	1753.0	244545
559	312481	174676879	23.6432	8.2377	2.74741	1.78891	1756.2	245422
560	313600	175616000	23.6643	8.2426	2.74819	78571	1759.3	246301
561	314721	176558481	23.6854	8.2475	2.74896	78253	1762.4	247181
562	315844	177504328	23.7065	8.2524	2.74974	77936	1765.6	248063
563	316969	178453547	23.7276	8.2573	2.75051	77620	1768.7	248947
564	318096	179406144	23.7487	8.2621	2.75128	1.77305	1771.9	249832
565	319225	180362125	23.7697	8.2670	2.75205	1.76991	1775.0	250719
566	320356	181321496	23.7908	8.2719	2.75282	1.76678	1778.1	251607
567	321489	182284263	23.8118	8.2768	2.75358	1.76367	1781.3	252497
568	322624	183250432	23.8328	8.2816	2.75435	1.76056	1784.4	253388
569	323761	184220009	23.8537	8.2865	2.75511	1.75747	1787.6	254281
570	324900	185193000	23.8747	8.2913	2.75587	75439	1790.7	255176
571	326041	186169411	23.8956	8.2962	2.75664	75131	1793.8	256072
572	327184	187149248	23.9165	8.3010	2.75740	74825	1797.0	256970
573	328329	188132517	23.9374	8.3059	2.75815	74520	1800.1	257869
574	329476	189119224	23.9583	8.3107	2.75891	1.74216	1803.3	258770
575	330625	190109375	23.9792	8.3155	2.75967	73913	1806.4	259672
576	331776	191102976	24.0000	8.3203	2.76042	73611	1809.6	260576
577	332929	192100033	24.0208	8.3251	2.76118	73310	1812.7	261482
578	334084	193100552	24.0416	8.3300	2.76193	73010	1815.8	262389
579	335241	194104539	24.0624	8.3348	2.76268	1.72712	1819.0	263298
580	336400	195112000	24.0832	8.3396	2.76343	.72414	1822.1	264208
581	337561	196122941	24.1039	8.3443	2.76418	.72117	1825.3	265120
582	338724	197137368	24.1247	8.3491	2.76492	.71821	1828.4	266033
583	339889	198155287	24.1454	8.3539	2.76567	.71527	1831.6	266948
584	341056	199176704	24.1661	8.3587	2.76641	1.71233	1834.7	267865
585	342225	200201625	24.1868	8.3634	2.76716	70940	1837.8	268783
586	343396	201230056	24.2074	8.3682	2.76790	70648	1841.0	269703
587	344569	202262003	24.2281	8.3730	2.76864	70358	1844.1	270624
588	345744	203297472	24.2487	8.3777	2.76938	70068	1847.3	271547
589	346921	204336469	24.2693	8.3825	2.77012	1.69779	1850.4	272471
590	348100	205379000	24.2899	8.3872	2.77085	.69492	1853.5	273397
591	349281	206425071	24.3105	8.3919	2.77159	.69205	1856.7	274325
592	350464	207474688	24.3311	8.3967	2.77232	.68919	1859.8	275254
593	351649	208527857	24.3516	8.4014	2.77305	.68634	1863.0	276184
594	352836	209584584	24.3721	8.4061	2.77379	1.68350	1866.1	277117
595	354025	210644875	24.3926	8.4108	2.77452	1.68067	1869.2	278051
596	355216	211708736	24.4131	8.4155	2.77525	1.67785	1872.4	278986
597	356409	212776173	24.4336	8.4202	2.77597	1.67504	1875.5	279923
598	357604	213847192	24.4540	8.4249	2.77670	1.67224	1878.7	280862
599	358801	214921799	24.4745	8.4296	2.77743	1.66945	1881.8	281802

FUNCTIONS OF NUMBERS

No.	Square	Cube	Square Root	Cube Root	Logarithm	1000 × Reciprocal	No. = Diameter	
							Circum.	Area
600	360000	216000000	24.4949	8.4343	2.77815	1.66667	1885.0	282743
601	361201	217081801	24.5153	8.4390	2.77887	1.66389	1888.1	283687
602	362404	218167208	24.5357	8.4437	2.77960	1.66113	1891.2	284631
603	363609	219256227	24.5561	8.4484	2.78032	1.65837	1894.4	285578
604	364816	220348864	24.5764	8.4530	2.78104	1.65563	1897.5	286526
605	366025	221445125	24.5967	8.4577	2.78176	1.65289	1900.7	287475
606	367236	222545016	24.6171	8.4623	2.78247	1.65017	1903.8	288426
607	368449	223648543	24.6374	8.4670	2.78319	1.64745	1906.9	289379
608	369664	224755712	24.6577	8.4716	2.78390	1.64474	1910.1	290333
609	370881	225866529	24.6779	8.4763	2.78462	1.64204	1913.2	291289
610	372100	226981000	24.6982	8.4809	2.78533	1.63934	1916.4	292247
611	373321	228099131	24.7184	8.4856	2.78604	1.63666	1919.5	293206
612	374544	229220928	24.7386	8.4902	2.78675	1.63399	1922.7	294166
613	375769	230346397	24.7588	8.4948	2.78746	1.63132	1925.8	295128
614	376996	231475544	24.7790	8.4994	2.78817	1.62866	1928.9	296092
615	378225	232608375	24.7992	8.5040	2.78888	1.62602	1932.1	297057
616	379456	233744896	24.8193	8.5086	2.78958	1.62338	1935.2	298024
617	380689	234885113	24.8395	8.5132	2.79029	1.62075	1938.4	298992
618	381924	236029032	24.8596	8.5178	2.79099	1.61812	1941.5	299962
619	383161	237176659	24.8797	8.5224	2.79169	1.61551	1944.6	300934
620	384400	238328000	24.8998	8.5270	2.79239	1.61290	1947.8	301907
621	385641	239483061	24.9199	8.5316	2.79309	1.61031	1950.9	302882
622	386884	240641848	24.9399	8.5362	2.79379	1.60772	1954.1	303858
623	388129	241804367	24.9600	8.5408	2.79449	1.60514	1957.2	304836
624	389376	242970624	24.9800	8.5453	2.79518	1.60256	1960.4	305815
625	390625	244140625	25.0000	8.5499	2.79588	1.60000	1963.5	306796
626	391876	245314376	25.0200	8.5544	2.79657	1.59744	1966.6	307779
627	393129	246491883	25.0400	8.5590	2.79727	1.59490	1969.8	308763
628	394384	247673152	25.0599	8.5635	2.79796	1.59236	1972.9	309748
629	395641	248858189	25.0799	8.5681	2.79865	1.58983	1976.1	310736
630	396900	250047000	25.0998	8.5726	2.79934	1.58730	1979.2	311725
631	398161	251239591	25.1197	8.5772	2.80003	1.58479	1982.3	312715
632	399424	252435968	25.1396	8.5817	2.80072	1.58228	1985.5	313707
633	400689	253636137	25.1595	8.5862	2.80140	1.57978	1988.6	314700
634	401956	254840104	25.1794	8.5907	2.80209	1.57729	1991.8	315696
635	403225	256047875	25.1992	8.5952	2.80277	1.57480	1994.9	316692
636	404496	257259456	25.2190	8.5997	2.80346	1.57233	1998.1	317690
637	405769	258474853	25.2389	8.6043	2.80414	1.56986	2001.2	318690
638	407044	259694072	25.2587	8.6088	2.80482	1.56740	2004.3	319692
639	408321	260917119	25.2784	8.6132	2.80550	1.56495	2007.5	320695
640	409600	262144000	25.2982	8.6177	2.80618	1.56250	2010.6	321699
641	410881	263374721	25.3180	8.6222	2.80686	1.56006	2013.8	322705
642	412164	264609288	25.3377	8.6267	2.80754	1.55763	2016.9	323713
643	413449	265847707	25.3574	8.6312	2.80821	1.55521	2020.0	324722
644	414736	267089984	25.3772	8.6357	2.80889	1.55280	2023.2	325733
645	416025	268336125	25.3969	8.6401	2.80956	1.55039	2026.3	326745
646	417316	269586136	25.4165	8.6446	2.81023	1.54799	2029.5	327759
647	418609	270840023	25.4362	8.6490	2.81090	1.54560	2032.6	328775
648	419904	272097792	25.4558	8.6535	2.81158	1.54321	2035.8	329792
649	421201	273359449	25.4755	8.6579	2.81224	1.54083	2038.9	330810

FUNCTIONS OF NUMBERS

No.	Square	Cube	Square Root	Cube Root	Logarithm	1000 × Reciprocal	No. = Diameter	
							Circum.	Area
650	422500	274625000	25.4951	8.6624	2.81291	53846	2042.0	331831
651	423801	275894451	25.5147	8.6668	2.81358	53610	2045.2	332853
652	425104	277167808	25.5343	8.6713	2.81425	53374	2048.3	333876
653	426409	278445077	25.5539	8.6757	2.81491	53139	2051.5	334901
654	427716	279726264	25.5734	8.6801	2.81558	1.52905	2054.6	335927
655	429025	281011375	25.5930	8.6845	2.81624	52672	2057.7	336955
656	430336	282300416	25.6125	8.6890	2.81690	52439	2060.9	337985
657	431649	283593393	25.6320	8.6934	2.81757	52207	2064.0	339016
658	432964	284890312	25.6515	8.6978	2.81823	51976	2067.2	340049
659	434281	286191179	25.6710	8.7022	2.81889	1.51745	2070.3	341084
660	435600	287496000	25.6905	8.7066	2.81954	51515	2073.5	342119
661	436921	288804781	25.7099	8.7110	2.82020	51286	2076.6	343157
662	438244	290117528	25.7294	8.7154	2.82086	51057	2079.7	344196
663	439569	291434247	25.7488	8.7198	2.82151	50830	2082.9	345237
664	440896	292754944	25.7682	8.7241	2.82217	1.50602	2086.0	346279
665	442225	294079625	25.7876	8.7285	2.82282	.50376	2089.2	347323
666	443556	295408296	25.8070	8.7329	2.82347	.50150	2092.3	348368
667	444889	296740963	25.8263	8.7373	2.82413	.49925	2095.4	349415
668	446224	298077632	25.8457	8.7416	2.82478	.49701	2098.6	350464
669	447561	299418309	25.8650	8.7460	2.82543	1.49477	2101.7	351514
670	448900	300763000	25.8844	8.7503	2.82607	49254	2104.9	352565
671	450241	302111711	25.9037	8.7547	2.82672	49031	2108.0	353618
672	451584	303464448	25.9230	8.7590	2.82737	48810	2111.2	354673
673	452929	304821217	25.9422	8.7634	2.82082	48588	2114.3	355730
674	454276	306182024	25.9615	8.7677	2.82866	1.48368	2117.4	356788
675	455625	307546875	25.9808	8.7721	2.82930	48148	2120.6	357847
676	456976	308915776	26.0000	8.7764	2.82995	47929	2123.7	358908
677	458329	310288733	26.0192	8.7807	2.83059	47710	2126.9	359971
678	459684	311665752	26.0384	8.7850	2.83123	47493	2130.0	361035
679	461041	313046839	26.0576	8.7893	2.83187	1.47275	2133.1	362101
680	462400	314432000	26.0768	8.7937	2.83251	47059	2136.3	363168
681	463761	315821241	26.0960	8.7980	2.83315	46843	2139.4	364237
682	465124	317214568	26.1151	8.8023	2.83378	46628	2142.6	365308
683	466489	318611987	26.1343	8.8066	2.83442	46413	2145.7	366380
684	467856	320013504	26.1534	8.8109	2.83506	1.46199	2148.8	367453
685	469225	321419125	26.1725	8.8152	2.83569	45985	2152.0	368528
686	470596	322828856	26.1916	8.8194	2.83632	45773	2155.1	369605
687	471969	324242703	26.2107	8.8237	2.83696	45560	2158.3	370684
688	473344	325660672	26.2298	8.8280	2.83759	45349	2161.4	371764
689	474721	327082769	26.2488	8.8323	2.83822	1.45138	2164.6	372845
690	476100	328509000	26.2679	8.8366	2.83885	44928	2167.7	373928
691	477481	329939371	26.2869	8.8408	2.83948	44718	2170.8	375013
692	478864	331373888	26.3059	8.8451	2.84011	44509	2174.0	376099
693	480249	332812557	26.3249	8.8493	2.84073	44300	2177.1	377187
694	481636	334255384	26.3439	8.8536	2.84136	1.44092	2180.3	378276
695	483025	335702375	26.3629	8.8578	2.84198	.43885	2183.4	379367
696	484416	337153536	26.3818	8.8621	2.84261	.43678	2186.5	380459
697	485809	338608873	26.4008	8.8663	2.84323	.43472	2189.7	381553
698	487204	340068392	26.4197	8.8706	2.84386	.43266	2192.8	382649
699	488601	341532099	26.4386	8.8748	2.84448	1.43062	2196.0	383746

FUNCTIONS OF NUMBERS

No.	Square	Cube	Square Root	Cube Root	Logarithm	1000 × Reciprocal	No. = Diameter	
							Circum.	Area
700	490000	343000000	26.4575	8.8790	2.84510	42857	2199.1	384845
701	491401	344472101	26.4764	8.8833	2.84572	42653	2202.3	385945
702	492804	345948408	26.4953	8.8875	2.84634	42450	2205.4	387047
703	494209	347428927	26.5141	8.8917	2.84696	42248	2208.5	388151
704	495616	348913664	26.5330	8.8959	2.84757	1.42045	2211.7	389256
705	497025	350402625	26.5518	8.9001	2.84819	.41844	2214.8	390363
706	498436	351895816	26.5707	8.9043	2.84880	.41643	2218.0	391471
707	499849	353393243	26.5895	8.9085	2.84942	.41443	2221.1	392580
708	501264	354894912	26.6083	8.9127	2.85003	.41243	2224.2	393692
709	502681	356400829	26.6271	8.9169	2.85065	.41044	2227.4	394805
710	504100	357911000	26.6458	8.9211	2.85126	40845	2230.5	395919
711	505521	359425431	26.6646	8.9253	2.85187	40647	2233.7	397035
712	506944	360944128	26.6833	8.9295	2.85248	40449	2236.8	398153
713	508369	362467097	26.7021	8.9337	2.85309	40252	2240.0	399272
714	509796	363994344	26.7208	8.9378	2.85370	1.40056	2243.1	400393
715	511225	365525875	26.7395	8.9420	2.85431	39860	2246.2	401515
716	512656	367061696	26.7582	8.9462	2.85491	39665	2249.4	402639
717	514089	368601813	26.7769	8.9503	2.85552	39470	2252.5	403765
718	515524	370146232	26.7955	8.9545	2.85612	39276	2255.7	404892
719	516961	371694959	26.8142	8.9587	2.85673	1.39082	2258.8	406020
720	518400	373248000	26.8328	8.9628	2.85733	38889	2261.9	407150
721	519841	374805361	26.8514	8.9670	2.85794	38696	2265.1	408282
722	521284	376367048	26.8701	8.9711	2.85854	38504	2268.2	409415
723	522729	377933067	26.8887	8.9752	2.85914	38313	2271.4	410550
724	524176	379503424	26.9072	8.9794	2.85974	1.38122	2274.5	411687
725	525625	381078125	26.9258	8.9835	2.86034	37931	2277.7	412825
726	527076	382657176	26.9444	8.9876	2.86094	37741	2280.8	413965
727	528529	384240583	26.9629	8.9918	2.86153	37552	2283.9	415106
728	529984	385828352	26.9815	8.9959	2.86213	37363	2287.1	416248
729	531441	387420489	27.0000	9.0000	2.86273	1.37174	2290.2	417393
730	532900	389017000	27.0185	9.0041	2.86332	.36986	2293.4	418539
731	534361	390617891	27.0370	9.0082	2.86392	.36799	2296.5	419686
732	535824	392223168	27.0555	9.0123	2.86451	.36612	2299.6	420835
733	537289	393832837	27.0740	9.0164	2.86510	.36426	2302.8	421986
734	538756	395446904	27.0924	9.0205	2.86570	1.36240	2305.9	423138
735	540225	397065375	27.1109	9.0246	2.86629	36054	2309.1	424293
736	541696	398688256	27.1293	9.0287	2.86688	35870	2312.2	425447
737	543169	400315553	27.1477	9.0328	2.86747	35685	2315.4	426604
738	544644	401947272	27.1662	9.0369	2.86806	35501	2318.5	427762
739	546121	403583419	27.1846	9.0410	2.86864	1.35318	2321.6	428922
740	547600	405224000	27.2029	9.0450	2.86923	.35135	2324.8	430084
741	549081	406869021	27.2213	9.0491	2.86982	34953	2327.9	431247
742	550564	408518488	27.2397	9.0532	2.87040	34771	2331.1	432412
743	552049	410172407	27.2580	9.0572	2.87099	34590	2334.2	433578
744	553536	411830784	27.2764	9.0613	2.87157	1.34409	2337.3	434746
745	555025	413493625	27.2947	9.0654	2.87216	34228	2340.5	435916
746	556516	415160936	27.3130	9.0694	2.87274	34048	2343.6	437087
747	558009	416832723	27.3313	9.0735	2.87332	33869	2346.8	438259
748	559504	418508992	27.3496	9.0775	2.87390	33690	2349.9	439433
749	561001	420189749	27.3679	9.0816	2.87448	1.33511	2353.1	440609

FUNCTIONS OF NUMBERS

No.	Square	Cube	Square Root	Cube Root	Logarithm	1000 × Reciprocal	No. = Diameter	
							Circum.	Area
750	562500	421875000	27.3861	9.0856	2.87506	1.33333	2356.2	441786
751	564001	423564751	27.4044	9.0896	2.87564	1.33156	2359.3	442965
752	565504	425259008	27.4226	9.0937	2.87622	1.32979	2362.5	444146
753	567009	426957777	27.4408	9.0977	2.87680	1.32802	2365.6	445328
754	568516	428661064	27.4591	9.1017	2.87737	1.32626	2368.8	446511
755	570025	430368875	27.4773	9.1057	2.87795	1.32450	2371.9	447697
756	571536	432081216	27.4955	9.1098	2.87852	1.32275	2375.0	448883
757	573049	433798093	27.5136	9.1138	2.87910	1.32100	2378.2	450072
758	574564	435519512	27.5318	9.1178	2.87967	1.31926	2381.3	451262
759	576081	437245479	27.5500	9.1218	2.88024	1.31752	2384.5	452453
760	577600	438976000	27.5681	9.1258	2.88081	1.31579	2387.6	453646
761	579121	440711081	27.5862	9.1298	2.88138	1.31406	2390.8	454841
762	580644	442450728	27.6043	9.1338	2.88196	1.31234	2393.9	456037
763	582169	444194947	27.6225	9.1378	2.88252	1.31062	2397.0	457234
764	583696	445943744	27.6405	9.1418	2.88309	1.30890	2400.2	458434
765	585225	447697125	27.6586	9.1458	2.88366	1.30719	2403.3	459635
766	586756	449455096	27.6767	9.1498	2.88423	1.30548	2406.5	460837
767	588289	451217663	27.6948	9.1537	2.88480	1.30378	2409.6	462041
768	589824	452984832	27.7128	9.1577	2.88536	1.30208	2412.7	463247
769	591361	454756609	27.7308	9.1617	2.88593	1.30039	2415.9	464454
770	592900	456533000	27.7489	9.1657	2.88649	1.29870	2419.0	465663
771	594441	458314011	27.7669	9.1696	2.88705	1.29702	2422.2	466873
772	595984	460099648	27.7849	9.1736	2.88762	1.29534	2425.3	468085
773	597529	461889917	27.8029	9.1775	2.88818	1.29366	2428.5	469298
774	599076	463684824	27.8209	9.1815	2.88874	1.29199	2431.6	470513
775	600625	465484375	27.8388	9.1855	2.88930	1.29032	2434.7	471730
776	602176	467288576	27.8568	9.1894	2.88986	1.28866	2437.9	472948
777	603729	469097433	27.8747	9.1933	2.89042	1.28700	2441.0	474168
778	605284	470910952	27.8927	9.1973	2.89098	1.28535	2444.2	475389
779	606841	472729139	27.9106	9.2012	2.89154	1.28370	2447.3	476612
780	608400	474552000	27.9285	9.2052	2.89209	1.28205	2450.4	477836
781	609961	476379541	27.9464	9.2091	2.89265	1.28041	2453.6	479062
782	611524	478211768	27.9643	9.2130	2.89321	1.27877	2456.7	480290
783	613089	480048687	27.9821	9.2170	2.89376	1.27714	2459.9	481519
784	614656	481890304	28.0000	9.2209	2.89432	1.27551	2463.0	482750
785	616225	483736625	28.0179	9.2248	2.89487	1.27389	2466.2	483982
786	617796	485587656	28.0357	9.2287	2.89542	1.27226	2469.3	485216
787	619369	487443403	28.0535	9.2326	2.89597	1.27065	2472.4	486451
788	620944	489303872	28.0713	9.2365	2.89653	1.26904	2475.6	487688
789	622521	491169069	28.0891	9.2404	2.89708	1.26743	2478.7	488927
790	624100	493039000	28.1069	9.2443	2.89763	1.26582	2481.9	490167
791	625681	494913671	28.1247	9.2482	2.89818	1.26422	2485.0	491409
792	627264	496793088	28.1425	9.2521	2.89873	1.26263	2488.1	492652
793	628849	498677257	28.1603	9.2560	2.89927	1.26103	2491.3	493897
794	630436	500566184	28.1780	9.2599	2.89982	1.25945	2494.4	495143
795	632025	502459875	28.1957	9.2638	2.90037	1.25786	2497.6	496391
796	633616	504358336	28.2135	9.2677	2.90091	1.25628	2500.7	497641
797	635209	506261573	28.2312	9.2716	2.90146	1.25471	2503.8	498892
798	636804	508169592	28.2489	9.2754	2.90200	1.25313	2507.0	500145
799	638401	510082399	28.2666	9.2793	2.90255	1.25156	2510.1	501399

FUNCTIONS OF NUMBERS

No.	Square	Cube	Square Root	Cube Root	Logarithm	1000 × Reciprocal	No. = Diameter	
							Circum.	Area
800	640000	512000000	28.2843	9.2832	2.90309	1.25000	2513.3	502655
801	641601	513922401	28.3019	9.2870	2.90363	1.24844	2516.4	503912
802	643204	515849608	28.3196	9.2909	2.90417	1.24688	2519.6	505171
803	644809	517781627	28.3373	9.2948	2.90472	1.24533	2522.7	506432
804	646416	519718464	28.3549	9.2986	2.90526	1.24378	2525.8	507694
805	648025	521660125	28.3725	9.3025	2.90580	1.24224	2529.0	508958
806	649636	523606616	28.3901	9.3063	2.90634	1.24069	2532.1	510223
807	651249	525557943	28.4077	9.3102	2.90687	1.23916	2535.3	411490
808	652864	527514112	28.4253	9.3140	2.90741	1.23762	2538.4	512758
809	654481	529475129	28.4429	9.3179	2.90795	1.23609	2541.5	514028
810	656100	531441000	28.4605	9.3217	2.90849	1.23457	2544.7	515300
811	657721	533411731	28.4781	9.3255	2.90902	1.23305	2547.8	516573
812	659344	535387328	28.4956	9.3294	2.90956	1.23153	2551.0	517848
813	660969	537367797	28.5132	9.3332	2.91009	1.23001	2554.1	519124
814	662596	539353144	28.5307	9.3370	2.91062	1.22850	2557.3	520402
815	664225	541343375	28.5482	9.3408	2.91116	1.22699	2560.4	521681
816	665856	543338496	28.5657	9.3447	2.91169	1.22549	2563.5	522962
817	667489	545338513	28.5832	9.3485	2.91222	1.22399	2566.7	524245
818	669124	547343432	28.6007	9.3523	2.91275	1.22249	2569.8	525529
819	670761	549353259	28.6182	9.3561	2.91328	1.22100	2573.0	526814
820	672400	551368000	28.6356	9.3599	2.91381	1.21951	2576.1	528102
821	674041	553387661	28.6531	9.3637	2.91434	1.21803	2579.2	529391
822	675684	555412248	28.6705	9.3675	2.91487	1.21655	2582.4	530681
823	677329	557441767	28.6880	9.3713	2.91540	1.21507	2585.5	531973
824	678976	559476224	28.7054	9.3751	2.91593	1.21359	2588.7	533267
825	680625	561515625	28.7228	9.3789	2.91645	1.21212	2591.8	534562
826	682276	563559976	28.7402	9.3827	2.91698	1.21065	2595.0	535858
827	683929	565609283	28.7576	9.3865	2.91751	1.20919	2598.1	537157
828	685584	567663552	28.7750	9.3902	2.91803	1.20773	2601.2	538456
829	687241	569722789	28.7924	9.3940	2.91855	1.20627	2604.4	539758
830	688900	571787000	28.8097	9.3978	2.91908	1.20482	2607.5	541061
831	690561	573856191	28.8271	9.4016	2.91960	1.20337	2610.7	542365
832	692224	575930368	28.8444	9.4053	2.92012	1.20192	2613.8	543671
833	693889	578009537	28.8617	9.4091	2.92065	1.20048	2616.9	544979
834	695556	580093704	28.8791	9.4129	2.92117	1.19904	2620.1	546288
835	697225	582182875	28.8964	9.4166	2.92169	1.19760	2623.2	547599
836	698896	584277056	28.9137	9.4204	2.92221	1.19617	2626.4	548912
837	700569	586376253	28.9310	9.4241	2.92273	1.19474	2629.5	550226
838	702244	588480472	28.9482	9.4279	2.92324	1.19332	2632.7	551541
839	703921	590589719	28.9655	9.4316	2.92376	1.19190	2635.8	552858
840	705600	592704000	28.9828	9.4354	2.92428	1.19048	2638.9	554177
841	707281	594823321	29.0000	9.4391	2.92480	1.18906	2642.1	555497
842	708964	596947688	29.0172	9.4429	2.92531	1.18765	2645.2	556819
843	710649	599077107	29.0345	9.4466	2.92583	1.18624	2648.4	558142
844	712336	601211584	29.0517	9.4503	2.92634	1.18483	2651.5	559467
845	714025	603351125	29.0689	9.4541	2.92686	1.18343	2654.6	560794
846	715716	605495736	29.0861	9.4578	2.92737	1.18203	2657.8	562122
847	717409	607645423	29.1033	9.4615	2.92788	1.18064	2660.9	563452
848	719104	609800192	29.1204	9.4652	2.92840	1.17925	2664.1	564783
849	720801	611960049	29.1376	9.4690	2.92891	1.17786	2667.2	566116

FUNCTIONS OF NUMBERS

No.	Square	Cube	Square Root	Cube Root	Logarithm	1000 × Reciprocal	No. = Diameter	
							Circum.	Area
850	722500	614125000	29.1548	9.4727	2.92942	1.17647	2670.4	567450
851	724201	616295051	29.1719	9.4764	2.92993	1.17509	2673.5	568786
852	725904	618470208	29.1890	9.4801	2.93044	1.17371	2676.6	570124
853	727609	620650477	29.2062	9.4838	2.93095	1.17233	2679.8	571463
854	729316	622835864	29.2233	9.4875	2.93146	1.17096	2682.9	572803
855	731025	625026375	29.2404	9.4912	2.93197	1.16959	2686.1	574146
856	732736	627222016	29.2575	9.4949	2.93247	1.16822	2689.2	575490
857	734449	629422793	29.2746	9.4986	2.93298	1.16686	2692.3	576835
858	736164	631628712	29.2916	9.5023	2.93349	1.16550	2695.5	578182
859	737881	633839779	29.3087	9.5060	2.93399	1.16414	2698.6	579530
860	739600	636056000	29.3258	9.5097	2.93450	1.16279	2701.8	580880
861	741321	638277381	29.3428	9.5134	2.93500	1.16144	2704.9	582232
862	743044	640503928	29.3598	9.5171	2.93551	1.16009	2708.1	583585
863	744769	642735647	29.3769	9.5207	2.93601	1.15875	2711.2	584940
864	746496	644972544	29.3939	9.5244	2.93651	1.15741	2714.3	586297
865	748225	647214625	29.4109	9.5281	2.93702	1.15607	2717.5	587655
866	749956	649461896	29.4279	9.5317	2.93752	1.15473	2720.6	589014
867	751689	651714363	29.4449	9.5354	2.93802	1.15340	2723.8	590375
868	753424	653972032	29.4618	9.5391	2.93852	1.15207	2726.9	591738
869	755161	656234909	29.4788	9.5427	2.93902	1.15075	2730.0	593102
870	756900	658503000	29.4958	9.5464	2.93952	1.14943	2733.2	594468
871	758641	660776311	29.5127	9.5501	2.94002	1.14811	2736.3	595835
872	760384	663054848	29.5296	9.5537	2.94052	1.14679	2739.5	597204
873	762129	665338617	29.5466	9.5574	2.94101	1.14548	2742.6	598575
874	763876	667627624	29.5635	9.5610	2.94151	1.14416	2745.8	599947
875	765625	669921875	29.5804	9.5647	2.94201	1.14286	2748.9	601320
876	767376	672221376	29.5973	9.5683	2.94250	1.14155	2752.0	602696
877	769129	674526133	29.6142	9.5719	2.94300	1.14025	2755.2	604073
878	770884	676836152	29.6311	9.5756	2.94349	1.13895	2758.3	605451
879	772641	679151439	29.6479	9.5792	2.94399	1.13766	2761.5	606831
880	774400	681472000	29.6648	9.5828	2.94448	1.13636	2764.6	608212
881	776161	683797841	29.6816	9.5865	2.94498	1.13507	2767.7	609595
882	777924	686128968	29.6985	9.5901	2.94547	1.13379	2770.9	610980
883	779689	688465387	29.7153	9.5937	2.94596	1.13250	2774.0	612366
884	781456	690807104	29.7321	9.5973	2.94645	1.13122	2777.2	613754
885	783225	693154125	29.7489	9.6010	2.94694	1.12994	2780.3	615143
886	784996	695506456	29.7658	9.6046	2.94743	1.12867	2783.5	616534
887	786769	697864103	29.7825	9.6082	2.94792	1.12740	2786.6	617927
888	788544	700227072	29.7993	9.6118	2.94841	1.12613	2789.7	619321
889	790321	702595369	29.8161	9.6154	2.94890	1.12486	2792.9	620717
890	792100	704969000	29.8329	9.6190	2.94939	1.12360	2796.0	622114
891	793881	707347971	29.8496	9.6226	2.94988	1.12233	2799.2	623513
892	795664	709732288	29.8664	9.6262	2.95036	1.12108	2802.3	624913
893	797449	712121957	29.8831	9.6298	2.95085	1.11982	2805.4	626315
894	799236	714516984	29.8998	9.6334	2.95134	1.11857	2808.6	627718
895	801025	716917375	29.9166	9.6370	2.95182	1.11732	2811.7	629124
896	802816	719323136	29.9333	9.6406	2.95231	1.11607	2814.9	630530
897	804609	721734273	29.9500	9.6442	2.95279	1.11483	2818.0	631938
898	806404	724150792	29.9666	9.6477	2.95328	1.11359	2821.2	633348
899	808201	726572699	29.9833	9.6513	2.95376	1.11235	2824.3	634760

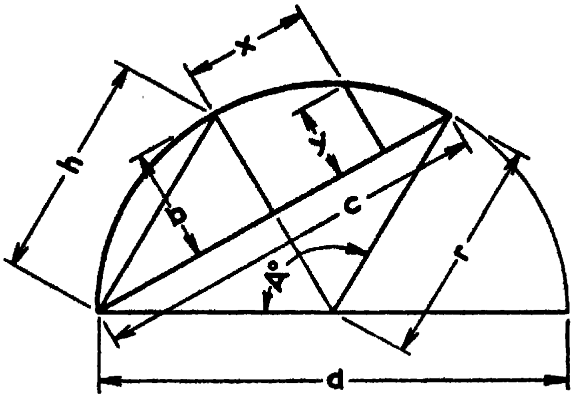
FUNCTIONS OF NUMBERS

No.	Square	Cube	Square Root	Cube Root	Logarithm	1000 × Reciprocal	No. = Diameter	
							Circum.	Area
900	810000	729000000	30.0000	9.6549	2.95424	1.11111	2827.4	636173
901	811801	731432701	30.0167	9.6585	2.95472	1.10988	2830.6	637587
902	813604	733870808	30.0333	9.6620	2.95521	1.10865	2833.7	639003
903	815409	736314327	30.0500	9.6656	2.95569	1.10742	2836.9	640421
904	817216	738763264	30.0666	9.6692	2.95617	1.10619	2840.0	641840
905	819025	741217625	30.0832	9.6727	2.95665	1.10497	2843.1	643261
906	820836	743677416	30.0998	9.6763	2.95713	1.10375	2846.3	644683
907	822649	746142643	30.1164	9.6799	2.95761	1.10254	2849.4	646107
908	824464	748613312	30.1330	9.6834	2.95809	1.10132	2852.6	647533
909	826281	751089429	30.1496	9.6870	2.95856	1.10011	2855.7	648960
910	828100	753571000	30.1662	9.6905	2.95904	1.09890	2858.8	650388
911	829921	756058031	30.1828	9.6941	2.95952	1.09769	2862.0	651818
912	831744	758550528	30.1993	9.6976	2.95999	1.09649	2865.1	653250
913	833569	761048497	30.2159	9.7012	2.96047	1.09529	2868.3	654684
914	835396	763551944	30.2324	9.7047	2.96095	1.09409	2871.4	656118
915	837225	766060875	30.2490	9.7082	2.96142	1.09290	2874.6	657555
916	839056	768575296	30.2655	9.7118	2.96190	1.09170	2877.7	658993
917	840889	771095213	30.2820	9.7153	2.96237	1.09051	2880.8	660433
918	842724	773620632	30.2985	9.7188	2.96284	1.08932	2884.0	661874
919	844561	776151559	30.3150	9.7224	2.96332	1.08814	2887.1	663317
920	846400	778688000	30.3315	9.7259	2.96379	1.08696	2890.3	664761
921	848241	781229961	30.3480	9.7294	2.96426	1.08578	2893.4	666207
922	850084	783777448	30.3645	9.7329	2.96473	1.08460	2896.5	667654
923	851929	786330467	30.3809	9.7364	2.96520	1.08342	2899.7	669103
924	853776	788889024	30.3974	9.7400	2.96567	1.08225	2902.8	670554
925	855625	791453125	30.4138	9.7435	2.96614	1.08108	2906.0	672006
926	857476	794022776	30.4302	9.7470	2.96661	1.07991	2909.1	673460
927	859329	796597983	30.4467	9.7505	2.96708	1.07875	2912.3	674915
928	861184	799178752	30.4631	9.7540	2.96755	1.07759	2915.4	676372
929	863041	801765089	30.4795	9.7575	2.96802	1.07643	2918.5	677831
930	864900	804357000	30.4959	9.7610	2.96848	1.07527	2921.7	679291
931	866761	806954491	30.5123	9.7645	2.96895	1.07411	2924.8	680752
932	868624	809557568	30.5287	9.7680	2.96942	1.07296	2928.0	682216
933	870489	812166237	30.5450	9.7715	2.96988	1.07181	2931.1	683680
934	872356	814780504	30.5614	9.7750	2.97035	1.07066	2934.2	685147
935	874225	817400375	30.5778	9.7785	2.97081	1.06952	2937.4	686615
936	876096	820025856	30.5941	9.7819	2.97128	1.06838	2940.5	688084
937	877969	822656953	30.6105	9.7854	2.97174	1.06724	2943.7	689555
938	879844	825293672	30.6268	9.7889	2.97220	1.06610	2946.8	691028
939	881721	827936019	30.6431	9.7924	2.97267	1.06496	2950.0	692502
940	883600	830584000	30.6594	9.7959	2.97313	1.06383	2953.1	693978
941	885481	833237621	30.6757	9.7993	2.97359	1.06270	2956.2	695455
942	887364	835896888	30.6920	9.8028	2.97405	1.06157	2959.4	696934
943	889249	838561807	30.7083	9.8063	2.97451	1.06045	2962.5	698415
944	891136	841232384	30.7246	9.8097	2.97497	1.05932	2965.7	699897
945	893025	843908625	30.7409	9.8132	2.97543	1.05820	2968.8	701380
946	894916	846590536	30.7571	9.8167	2.97589	1.05708	2971.9	702865
947	896809	849278123	30.7734	9.8201	2.97635	1.05597	2975.1	704352
948	898704	851971392	30.7896	9.8236	2.97681	1.05485	2978.2	705840
949	900601	854670349	30.8058	9.8270	2.97727	1.05374	2981.4	707330

FUNCTIONS OF NUMBERS

No.	Square	Cube	Square Root	Cube Root	Logarithm	1000 × Reciprocal	No. = Diameter Circum.	No. = Diameter Area
950	902500	857375000	30.8221	9.8305	2.97772	05263	2984.5	708822
951	904401	860085351	30.8383	9.8339	2.97818	05152	2987.7	710315
952	906304	862801408	30.8545	9.8374	2.97864	05042	2990.8	711809
953	908209	865523177	30.8707	9.8408	2.97909	04932	2993.9	713306
954	910116	868250664	30.8869	9.8443	2.97955	1.04822	2997.1	714803
955	912025	870983875	30.9031	9.8477	2.98000	04712	3000.2	716303
956	913936	873722816	30.9192	9.8511	2.98046	04603	3003.4	717804
957	915849	876467493	30.9354	9.8546	2.98091	04493	3006.5	719306
958	917764	879217912	30.9516	9.8580	2.98137	04384	3009.6	720810
959	919681	881974079	30.9677	9.8614	2.98182	1.04275	3012.8	722316
960	921600	884736000	30.9839	9.8648	2.98227	.04167	3015.9	723823
961	923521	887503681	31.0000	9.8683	2.98272	.04058	3019.1	725332
962	925444	890277128	31.0161	9.8717	2.98318	.03950	3022.2	726842
963	927369	893056347	31.0322	9.8751	2.98363	.03842	3025.4	728354
964	929296	895841344	31.0483	9.8785	2.98408	1.03734	3028.5	729867
965	931225	898632125	31.0644	9.8819	2.98453	03627	3031.6	731382
966	933156	901428696	31.0805	9.8854	2.98498	03520	3034.8	732899
967	935089	904231063	31.0966	9.8888	2.98543	03413	3037.9	734417
968	937024	907039232	31.1127	9.8922	2.98588	03306	3041.1	735937
969	938961	909853209	31.1288	9.8956	2.98632	1.03199	3044.2	737458
970	940900	912673000	31.1448	9.8990	2.98677	.03093	3047.3	738981
971	942841	915498611	31.1609	9.9024	2.98722	.02987	3050.5	740506
972	944784	918330048	31.1769	9.9058	2.98767	.02881	3053.6	742032
973	946729	921167317	31.1929	9.9092	2.98811	.02775	3056.8	743559
974	948676	924010424	31.2090	9.9126	2.98856	1.02669	3059.9	745088
975	950625	926859375	31.2250	9.9160	2.98900	02564	3063.1	746619
976	952576	929714176	31.2410	9.9194	2.98945	02459	3066.2	748151
977	954529	932574833	31.2570	9.9227	2.98989	02354	3069.3	749685
978	956484	935441352	31.2730	9.9261	2.99034	02249	3072.5	751221
979	958441	938313739	31.2890	9.9295	2.99078	1.02145	3075.6	752758
980	960400	941192000	31.3050	9.9329	2.99123	.02041	3078.8	754296
981	962361	944076141	31.3209	9.9363	2.99167	.01937	3081.9	755837
982	964324	946966168	31.3369	9.9396	2.99211	.01833	3085.0	757378
983	966289	949862087	31.3528	9.9430	2.99255	.01729	3088.2	758922
984	968256	952763904	31.3688	9.9464	2.99300	1.01626	3091.3	760466
985	970225	955671625	31.3847	9.9497	2.99344	01523	3094.5	762013
986	972196	958585256	31.4006	9.9531	2.99388	01420	3097.6	763561
987	974169	961504803	31.4166	9.9565	2.99432	01317	3100.8	765111
988	976144	964430272	31.4325	9.9598	2.99476	01215	3103.9	766662
989	978121	967361669	31.4484	9.9632	2.99520	1.01112	3107.0	768214
990	980100	970299000	31.4643	9.9666	2.99564	.01010	3110.2	769769
991	982081	973242271	31.4802	9.9699	2.99607	.00908	3113.3	771325
992	984064	976191488	31.4960	9.9733	2.99651	.00806	3116.5	772882
993	986049	979146657	31.5119	9.9766	2.99695	.00705	3119.6	774441
994	988036	982107784	31.5278	9.9800	2.99739	1.00604	3122.7	776002
995	990025	985074875	31.5436	9.9833	2.99782	.00503	3125.9	777564
996	992016	988047936	31.5595	9.9866	2.99826	.00402	3129.0	779128
997	994009	991026973	31.5753	9.9900	2.99870	.00301	3132.2	780693
998	996004	994011992	31.5911	9.9933	2.99913	.00200	3135.3	78
999	998001	997002999	31.6070	9.9967	2.99957	1.00100	3138.5	

PROPERTIES OF THE CIRCLE



Circumference = 6.28318 r = 3.14159 d
Diameter = 0.31831 circumference
Area = 3.14159 r²

Arc $a = \frac{\pi r A^\circ}{180^\circ} = 0.017453\ r A^\circ = \frac{8h - c}{3}$ (approximately)

Angle $A^\circ = \frac{180^\circ a}{\pi r} = 57.29578 \frac{a}{r}$

Radius $r = \frac{4b^2 + c^2}{8b}$

Diameter $d = \frac{h^2}{b} = \frac{c^2}{4b} + b$

Chord $c = 2\sqrt{2br - b^2} = 2r \sin\frac{A}{2}$

$= 2\sqrt{h^2 - b^2} = 2\sqrt{(d - b) \times b}$

Chord of ½ the arc h $\sqrt{d \times b} = \frac{3a + c}{8}$ (approximately)

Rise $b = r - \frac{1}{2}\sqrt{4r^2 - c^2} = \frac{c}{2}\tan\frac{A}{4}$

$2r \sin^2\frac{A}{4} \quad r + y - \sqrt{r^2 - x^2} = \frac{h^2}{d}$

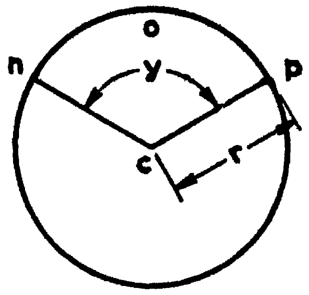
$y = b - r + \sqrt{r^2 - x^2}$

$x \quad \sqrt{r^2 - (r + y - b)^2}$

Diameter of circle of equal periphery as square = 1.27324 side of square
Side of square of equal periphery as circle = 0.78540 diameter of circle
Diameter of circle circumscribed about square = 1.41421 side of square
Side of square inscribed in circle = 0.70711 diameter of circle
Side of square of equal area = 0.8862 diameter of circle

PROPERTIES OF THE CIRCLE

CIRCULAR SECTOR



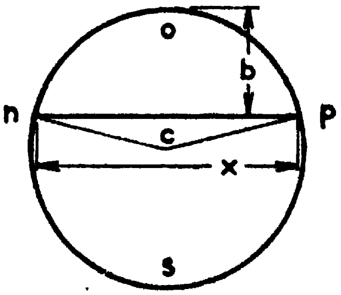
r = radius of circle y = angle ncp in degrees

Area of Sector ncpo = ½ (length of arc nop × r)

$$= \text{Area of Circle} \times \frac{y}{360}$$

$$= 0.0087266 \times r^2 \times y$$

CIRCULAR SEGMENT



r = radius of circle x = chord b = rise

Area of Segment nop = Area of Sector ncpo − Area of triangle ncp

$$= \frac{(\text{Length of arc nop} \times r) - x\,(r - b)}{2}$$

Area of Segment nsp = Area of Circle − Area of Segment nop

VALUES FOR FUNCTIONS OF π

	3.14159265359,	log = 0.4971499	$\frac{1}{\pi^2}$ =	0.1013212,	log = $\bar{1}.0057003$
π^2 =	9.8696044,	log = 0.9942997		0.0322515,	log = $\bar{2}.5085500$
π^3 =	31.0062767,	log = 1.4914496	$\sqrt{\frac{1}{\pi}}$	0.5641896,	log = $\bar{1}.7514251$
$\sqrt{\pi}$ =	1.7724539,	log = 0.2485749	$\frac{\pi}{180}$ =	0.0174533,	log = $\bar{2}.2418774$
$\frac{1}{\pi}$ =	0.3183099,	log = $\bar{1}.5028501$	$\frac{180}{\pi}$ =	57.2957795,	log = 1.7581226

AREAS AND VOLUMES

PLANE SURFACES

Ellipse

Area = $\frac{1}{4}\pi AB$, A and B being length and breadth (major and minor axes) respectively.

Triangle

Area = $\frac{1}{2}$ base × altitude

= $\sqrt{S(S-A)(S-B)(S-C)}$, $S = \frac{1}{2}$ sum of 3 sides, A, B, and C.

Trapezium

Area = sum of area of its 2 triangles.

Trapezoid

Area = $\frac{1}{2}$ sum of parallel sides × perpendicular height.

Parallelogram

Area = base × perpendicular height.

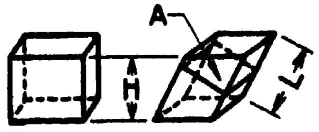
Regular Polygon

Area = $\frac{1}{2}$ sum of sides × inside radius.

Distance across corners of hexagon = 1.155 × distance across flats.

LATERAL SURFACES (S) AND VOLUMES (V) OF VARIOUS GEOMETRIC SOLIDS

Parallelopiped

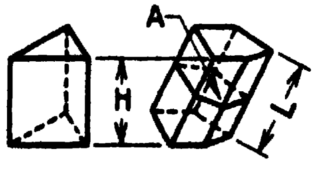


S = perimeter, P, perpendicular to sides × lateral length, L = PL

V = area of base, B, × perpendicular height, H = BH

V = area of section, A, perpendicular to sides × lateral length, L = AL

Prism, Right or Oblique, Regular or Irregular

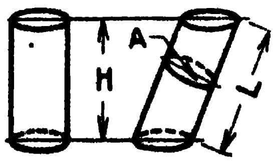


S = perimeter, P, perpendicular to sides × lateral length, L = PL

V = area of base, B, × perpendicular height, H = BH

V = area of section, A, perpendicular to sides × lateral length, L = AL

Cylinder, Right or Oblique, Circular or Elliptical



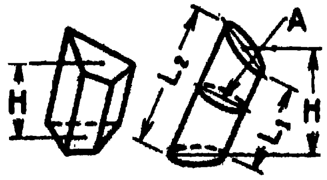
S = perimeter of base, P, × perpendicular height, H = PH

S = perimeter, P_1, perpendicular to sides × lateral length, L = P_1L

V = area of base, B, × perpendicular height, H = BH

V = area of section, A, perpendicular to sides × lateral length, L = AL

Frustum of Any Prism or Cylinder



V = area of base, B, × perpendicular distance, H, from base to center of gravity of opposite face = BH

For cylinder: $V = \frac{1}{2}A(L_1 + L_2)$

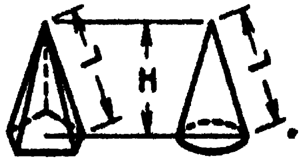
AREAS AND VOLUMES

(CONTINUED)

LATERAL SURFACES (S) AND VOLUMES (V) OF VARIOUS GEOMETRIC SOLIDS

(CONTINUED)

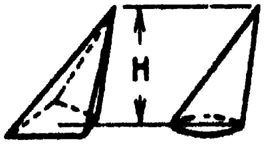
Pyramid or Cone, Right and Regular



S = perimeter of base, P, × $\frac{1}{2}$ slant height, L = $\frac{1}{2}PL$

V = area of base, B, × $\frac{1}{3}$ perpendicular height, H = $\frac{1}{3}BH$

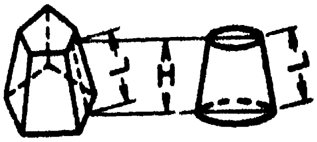
Pyramid or Cone, Right or Oblique, Regular or Irregular



V = area of base, B × $\frac{1}{3}$ perpendicular height, H = $\frac{1}{3}BH$

V = $\frac{1}{3}$ volume of prism or cylinder of same base and perpendicular height

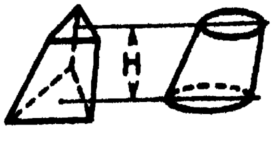
Frustum of Pyramid or Cone, Right and Regular, Parallel Ends



S = (sum of perimeter of base, P, and top, p) × $\frac{1}{2}$ slant height, L = $\frac{1}{2}L(P + p)$

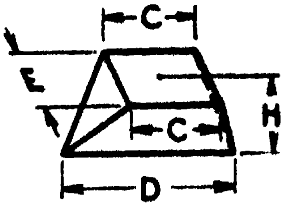
V = (sum of areas of base, B, and top, b, plus square root of their products) × $\frac{1}{3}$ perpendicular height, H = $\frac{1}{3}H(B + b + \sqrt{Bb})$

Frustum of Any Pyramid or Cone, Parallel Ends



V = (sum of areas of base, B, and top, b, plus square root of their products) × $\frac{1}{3}$ perpendicular height, H = $\frac{1}{3}H(B + b + \sqrt{Bb})$

Wedge. Parallelogram Face



$\frac{1}{6}$ (sum of three edges, C D C, × perpendicular height, H, × perpendicular width, E) = $\frac{1}{6}EH(2C + D)$

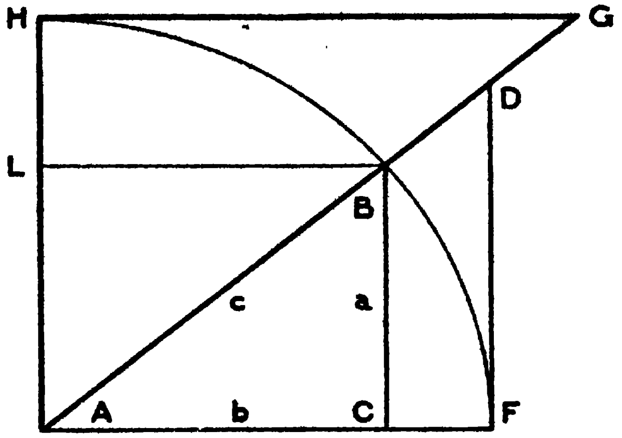
Sphere

4 × π × square of radius, R = $4\pi R^2$ = π × square of diameter, D = πD^2

$1\frac{1}{3}$ × π × cube of radius, R = $1\frac{1}{3}\pi R^3$ = $\frac{1}{6}$ × π × cube of diameter, D = $\frac{1}{6}\pi D^3$

TRIGONOMETRIC FORMULAS

TRIGONOMETRIC FUNCTIONS



Radius AF $= 1$

$= \sin^2 A = \cos^2 A = \sin A \operatorname{cosec} A$

$= \cos A \sec A = \tan A \cot A$

Sine A $= \dfrac{\cos A}{\cot A} = \dfrac{1}{\operatorname{cosec} A} = \cos A \tan A = \sqrt{1 - \cos^2 A} =$ BC

Cosine A $\dfrac{\sin A}{\tan A} \quad \dfrac{1}{\sec A} = \sin A \cot A = \sqrt{1 - \sin^2 A} =$ AC

Tangent A $= \dfrac{\sin A}{\cos A} - \dfrac{1}{\cot A} = \sin A \sec A$ FD

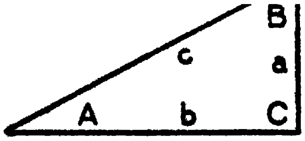
Cotangent A $= \dfrac{\cos A}{\sin A} = \dfrac{1}{\tan A} = \cos A \operatorname{cosec} A$ HG

Secant A $\dfrac{\tan A}{\sin A} = \dfrac{1}{\cos A}$ AD

Cosecant A $= \dfrac{\cot A}{\cos A} = \dfrac{1}{\sin A}$ AG

TRIGONOMETRIC FORMULAS

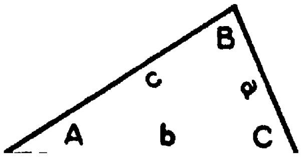
RIGHT-ANGLED TRIANGLES



$$a^2 = c^2 - b^2$$
$$b^2 = c^2 - a^2$$
$$c^2 = a^2 + b^2$$

Known	Required					
	A	B	a	b	c	Area
a, b	$\tan A = \frac{a}{b}$	$\tan B = \frac{b}{a}$			$\sqrt{a^2 + b^2}$	$\frac{ab}{2}$
a, c	$\sin A = \frac{a}{c}$	$\cos B = \frac{a}{c}$		$\sqrt{c^2 - a^2}$		$\frac{a\sqrt{c^2 - a^2}}{2}$
A, a		$90° - A$		$a \cot A$	$\frac{a}{\sin A}$	$\frac{a^2 \cot A}{2}$
A, b		$90° - A$	$b \tan A$		$\frac{b}{\cos A}$	$\frac{b^2 \tan A}{2}$
A, c		$90° - A$	$c \sin A$	$c \cos A$		$\frac{c^2 \sin 2A}{4}$

OBLIQUE-ANGLED TRIANGLES



$$s = a + b + c$$

$$a^2 = b^2 + c^2 - 2bc \cos A$$
$$b^2 = a^2 + c^2 - 2ac \cos B$$
$$c^2 = a^2 + b^2 - 2ab \cos C$$

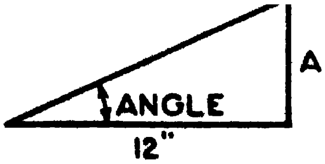
Known	Required		
	A	B	C
a, b, c	$\cos \frac{1}{2} A = \sqrt{\frac{s(s-a)}{bc}}$	$\cos \frac{1}{2} B = \sqrt{\frac{s(s-b)}{ac}}$	$\cos \frac{1}{2} C = \sqrt{\frac{s(s-c)}{ab}}$
a, A, B			$180° - (A + B)$
a, b, A		$\sin B = \frac{b \sin A}{a}$	
a, b, C	$\tan A = \frac{a \sin C}{b - a \cos C}$		

Known	Required		
	b		Area
a, b, c			$\sqrt{s(s-a)(s-b)(s-c)}$
a, A, B	$\frac{a \sin B}{\sin A}$	$\frac{a \sin C}{\sin A}$	
a, b, A		$\frac{b \sin C}{\sin B}$	
a, b, C		$\sqrt{a^2 + b^2 - 2ab \cos C}$	$\frac{ab \sin C}{2}$

NATURAL TRIGONOMETRIC FUNCTIONS

Deg.	Sin	Cos	Tan	Ctn	Sec	Csc	
0	0.0000	1.0000	0.0000	. . . . . .	1.0000	. . . . . .	90
1	0.0175	0.9998	0.0175	57.290	1.0002	57.299	89
2	0.0349	0.9994	0.0349	28.636	1.0006	28.654	88
3	0.0523	0.9986	0.0524	19.081	1.0014	19.107	87
4	0.0698	0.9976	0.0699	14.301	1.0024	14.336	86
5	0.0872	0.9962	0.0875	11.430	1.0038	11.474	85
6	0.1045	0.9945	0.1051	9.5144	1.0055	9.5668	84
7	0.1219	0.9925	0.1228	8.1443	1.0075	8.2055	83
8	0.1392	0.9903	0.1405	7.1154	1.0098	7.1853	82
9	0.1564	0.9877	0.1584	6.3138	1.0125	6.3925	81
10	0.1736	0.9848	0.1763	6.6713	1.0154	5.7588	80
11	0.1908	0.9816	0.1944	5.1446	1.0187	5.2408	79
12	0.2079	0.9781	0.2126	4.7046	1.0223	4.8097	78
13	0.2250	0.9744	0.2309	4.3315	1.0263	4.4454	77
14	0.2419	0.9703	0.2493	4.0108	1.0306	4.1336	76
15	0.2588	0.9659	0.2679	3.7321	1.0353	3.8637	75
16	0.2756	0.9613	0.2867	3.4874	1.0403	3.6280	74
17	0.2924	0.9563	0.3057	3.2709	1.0457	3.4203	73
18	0.3090	0.9511	0.3249	3.0777	1.0515	3.2361	72
19	0.3256	0.9455	0.3443	2.9042	1.0576	3.0716	71
20	0.3420	0.9397	0.3640	2.7475	1.0642	2.9238	70
21	0.3584	0.9336	0.3839	2.6051	1.0711	2.7904	69
22	0.3746	0.9272	0.4040	2.4751	1.0785	2.6695	68
23	0.3907	0.9205	0.4245	2.3559	1.0864	2.5593	67
24	0.4067	0.9135	0.4452	2.2460	1.0946	2.4586	66
25	0.4226	0.9063	0.4663	2.1445	1.1034	2.3662	65
26	0.4384	0.8988	0.4877	2.0503	1.1126	2.2812	64
27	0.4540	0.8910	0.5095	1.9626	1.1223	2.2027	63
28	0.4695	0.8829	0.5317	1.8807	1.1326	2.1301	62
29	0.4848	0.8746	0.5543	1.8040	1.1434	2.0627	61
30	0.5000	0.8660	0.5774	1.7321	1.1547	2.0000	60
31	0.5150	0.8572	0.6009	1.6643	1.1666	1.9416	59
32	0.5299	0.8480	0.6249	1.6003	1.1792	1.8871	58
33	0.5446	0.8387	0.6494	1.5399	1.1924	1.8361	57
34	0.5592	0.8290	0.6745	1.4826	1.2062	1.7883	56
35	0.5736	0.8192	0.7002	1.4281	1.2208	1.7434	55
36	0.5878	0.8090	0.7265	1.3764	1.2361	1.7013	54
37	0.6018	0.7986	0.7536	1.3270	1.2521	1.6616	53
38	0.6157	0.7880	0.7813	1.2799	1.2690	1.6243	52
39	0.6293	0.7771	0.8098	1.2349	1.2868	1.5890	51
40	0.6428	0.7660	0.8391	1.1918	1.3054	1.5557	50
41	0.6561	0.7547	0.8693	1.1504	1.3250	1.5243	49
42	0.6691	0.7431	0.9004	1.1106	1.3456	1.4945	48
43	0.6820	0.7314	0.9325	1.0724	1.3673	1.4663	47
44	0.6947	0.7193	0.9657	1.0355	1.3902	1.4396	46
45	0.7071	0.7071	1.0000	1.0000	1.4142	1.4142	45
	Cos	Sin	Ctn	Tan	Csc	Sec	Deg.

BEVELS



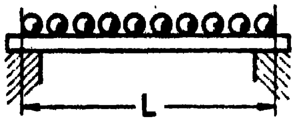
Rise A, Inches	RISE A — INCHES											
	0		1		2		3		4		5	
	Angle		Angle		Angle		Angle		Angle		Angle	
	Deg.	Min.	Deg.	Min.	Deg.	Min.	Deg.	Min.	Deg.	Min.	Deg.	Min.
0	.....	.....	4	46	9	28	14	02	18	26	22	37
1/16	0	18	5	04	9	45	14	19	18	42	22	52
1/8	0	36	5	21	10	03	14	36	18	58	23	08
3/16	0	54	5	39	10	20	14	53	19	14	23	23
1/4	1	12	5	57	10	37	15	09	19	30	23	38
5/16	1	30	6	15	10	54	15	26	19	46	23	53
3/8	1	47	6	32	11	12	15	43	20	02	24	08
7/16	2	05	6	50	11	29	15	59	20	18	24	23
1/2	2	23	7	08	11	46	16	16	20	33	24	37
9/16	2	41	7	25	12	03	16	32	20	49	24	52
5/8	2	59	7	43	12	20	16	49	21	05	25	07
11/16	3	17	8	00	12	37	17	05	21	20	25	22
3/4	3	35	8	18	12	54	17	21	21	36	25	36
13/16	3	52	8	35	13	11	17	38	21	51	25	51
7/8	4	10	8	53	13	28	17	54	22	07	26	05
15/16	4	28	9	10	13	45	18	10	22	22	26	20

Rise A, Inches	RISE A — INCHES											
	6		7		8		9		10		11	
	Angle		Angle		Angle		Angle		Angle		Angle	
	Deg.	Min.	Deg.	Min.	Deg.	Min.	Deg.	Min.	Deg.	Min.	Deg.	Min.
0	26	34	30	15	33	41	36	52	39	48	42	31
1/16	26	48	30	29	33	54	37	04	39	59	42	40
1/8	27	02	30	42	34	06	37	15	40	09	42	50
3/16	27	17	30	55	34	18	37	26	40	20	43	00
1/4	27	31	31	08	34	31	37	38	40	30	43	09
5/16	27	45	31	21	34	43	37	49	40	41	43	19
3/8	27	59	31	34	34	55	38	00	40	51	43	28
7/16	28	13	31	47	35	07	38	11	41	01	43	38
1/2	28	27	32	00	35	19	38	22	41	11	43	47
9/16	28	40	32	13	35	31	38	33	41	21	43	56
5/8	28	54	32	26	35	42	38	44	41	31	44	05
11/16	29	08	32	39	35	54	38	55	41	41	44	15
3/4	29	21	32	51	36	06	39	06	41	51	44	24
13/16	29	35	33	04	36	18	39	16	42	01	44	33
7/8	29	49	33	17	36	29	39	27	42	11	44	42
15/16	30	02	33	29	36	41	39	38	42	21	44	51

BEAM FORMULAS

$W = W_1 + W_2 =$ **Total load**, in pounds, uniformly distributed, including weight of beam.
$W_1 =$ Total **superimposed** or **live load**, in pounds, uniformly distributed.
$W_2 =$ Total **weight** of beam or **dead load**, in pounds, uniformly distributed.
$M =$ Maximum bending moment, inch-pounds.
$R =$ Maximum shear at point or points of support, in pounds.
$P =$ **Load** in pounds, concentrated at any points.
$L =$ **Length** of span, in inches.
$I =$ **Moment of inertia**, in inches^4
$E =$ **Modulus of elasticity**, in pounds per square inch (steel = 29,000,000).
$D =$ Maximum deflection of beam in inches.

(1) Beam Supported at Both Ends and Uniformly Loaded.

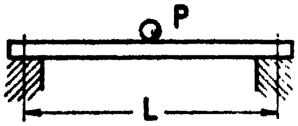


$$M = \frac{WL}{8}$$

$$R = \frac{W}{2}$$

$$D = \frac{5\,WL^3}{384\,EI}$$

(2) Beam Supported at Both Ends with Load Concentrated at the Middle.

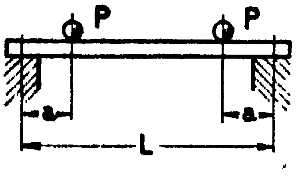


$$M = \frac{PL}{4} + \frac{W_2L}{8}$$

$$R = \frac{P + W_2}{2}$$

$$\frac{PL^3}{48\,EI} + \frac{5\,W_2L^3}{384\,EI}$$

(3) Beam Supported at Both Ends with Two Symmetrical Loads.



$$M \quad Pa + \frac{W_2L}{8}$$

$$R \quad 2\,P + W_2$$

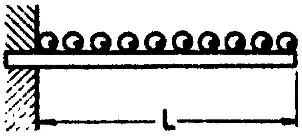
$$\frac{Pa(3\,L^2 - 4\,a^2)}{24\,EI} + \frac{5\,W_2L^3}{384EI}$$

BEAM FORMULAS

(CONTINUED)

(FOR NOTATIONS, SEE OPPOSITE PAGE)

(4) Beam Fixed at One End, Unsupported at the Other, and Uniformly Loaded.

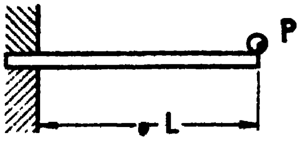


$$M = \frac{WL}{2}$$

$$R = W$$

$$D = \frac{WL^3}{8\,EI}$$

(5) Beam Fixed at One End, Unsupported at the Other, with Load Concentrated at the Free End.

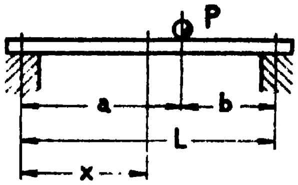


$$M = PL + {}^{W}$$

$$R = P + W_2$$

$$D = \frac{PL^3}{3\,EI} + \frac{W_2L^3}{8\,EI}$$

(6) Beam Supported at Both Ends with Load Concentrated at Any Point.



$$M \quad \frac{a(2\,Pb + W_2L - W_2a)}{2\,L}$$

Max. shear at nearest support

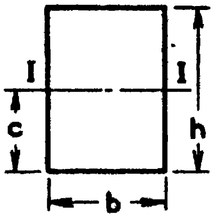
$$R \quad \frac{Pa}{L} + \frac{W_2}{2}$$

$$\frac{1}{3\,EIL}\left[\frac{2\,aL - a^2}{3}\right]^{\frac{3}{2}}\left[Pb + \frac{W_2}{8}\left(\sqrt{2\,aL - a^2} + \frac{3\,L^3}{2\,aL - a^2} - 2\,L\right)\right]$$

Distance "x", from left support to point of maximum deflection for superimposed load $\sqrt{2\,aL - a^2}$

SECTION ELEMENTS

A = area. I = moment of inertia about axis shown. c = distance from axis to remotest point of the section. I/c = section modulus. r = radius of gyration.



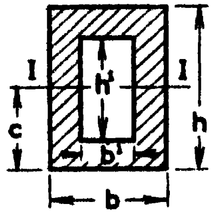
Rectangle

Axis through center.

$A = bh \qquad I = \frac{bh^3}{12}$

$c = \frac{h}{2} \qquad \frac{I}{c} = \frac{bh^2}{6}$

$r = \frac{h}{\sqrt{12}} = 0.289\ h$



Hollow Rectangle

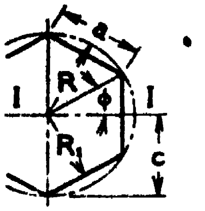
Axis through center.

$A = bh - b_1h_1$

$I = \frac{bh^3 - b_1h_1^3}{12} \qquad c = \frac{h}{2}$

$\frac{I}{c} = \frac{bh^3 - b_1h_1^3}{6\,h}$

$r = \sqrt{\frac{bh^3 - b_1h_1^3}{12(bh - b_1h_1)}}$



Regular Polygon

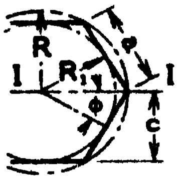
Axis through center normal to side. n = even number of sides
$A = nR_1^2 \tan \phi$

$c = R = \frac{a}{2 \sin \phi}$

$I = \frac{A(6\,R^2 - a^2)}{24}$

$\frac{I}{c} = \frac{A(6\,R^2 - a^2)}{24\,R}$

$r = \sqrt{\frac{6\,R^2 - a^2}{24}}$



Regular Polygon

Axis through center parallel to one side.

n = even number of sides.

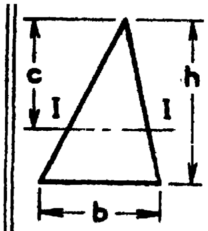
$A = nR_1^2 \tan \phi$

$c = R_1 = \frac{a}{2 \tan \phi}$

$I = \frac{A(12\,R_1^2 + a^2)}{48}$

$\frac{I}{c} = \frac{A(12\,R_1^2 + a^2)}{48\,R_1}$

$r = \sqrt{\frac{12\,R_1^2 + a^2}{48}}$



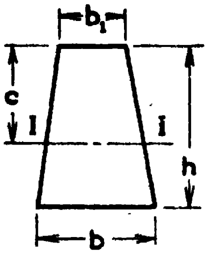
Triangle

Axis through center of gravity

$A = \frac{bh}{2} \qquad I = \frac{bh^3}{36}$

$c = \frac{2}{3}\,h \qquad \frac{I}{c} = \frac{bh^2}{24}$

$r = \frac{h}{\sqrt{18}} = 0.236\ h$



Trapezoid

Axis through center of gravity

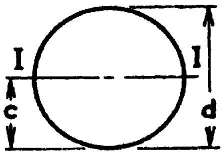
$A = \frac{(b + b_1)h}{2}$

$c = \frac{(b_1 + 2\,b)h}{3(b + b_1)}$

$I = \frac{h^3(b^2 + 4\,bb_1 + b_1^2)}{36(b + b_1)}$

$\frac{I}{c} = \frac{h^2(b^2 + 4\,bb_1 + b_1^2)}{12(b_1 + 2\,b)}$

$r = \frac{h\sqrt{2(b^2 + 4\,bb_1 + b_1^2)}}{6(b + b_1)}$



Circle

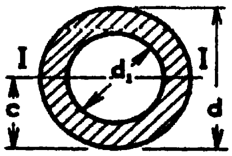
Axis through center.

$A = \frac{\pi d^2}{4} = 0.7854\ d^2$

$c = \frac{d}{2} \qquad r = \frac{d}{4}$

$I = \frac{\pi d^4}{64} = 0.0491\ d^4$

$\frac{I}{c} = \frac{\pi d^3}{32} = 0.0982\ d^3$



Hollow Circle

Axis through center.

$A = \frac{\pi(d^2 - d_1^2)}{4}$

$= 0.7854\ (d^2 - d_1^2)$

$c = \frac{d}{2}$

$I = \frac{\pi(d^4 - d_1^4)}{64}$

$\frac{I}{c} = \frac{\pi(d^4 - d_1^4)}{32\,d}$

$r = \frac{\sqrt{d^2 + d_1^2}}{4}$

ENGINEERING CONSTANTS

Existing engineering handbooks are remarkably complete in the matter of engineering constants; this table does not pretend to compete with them in their natural field. It frequently happens, however, that the reader of technical journals and books runs across a constant, the meaning of which is not clear to him. Often there is no clue to aid him in locating it in the engineering handbooks. On this page and the following two pages a large number of the more important constants are arranged numerically (regardless of the position of the decimal point) so that a given constant may be located almost instantly. An asterisk (*) means that the constant is exact as far as given, being generally either a mathematical constant or one fixed by definition. Where the first constant given is followed by another in parenthesis, the first is the round number ordinarily used and the second the more exact value.

0* deg. C. = freezing point of water

1 = atomic wgt. hydrogen

100* deg. C. = boiling point of water at atm. press.

10.764* sq. ft. = 1 sq. meter

0.1134 hp. = available water power from 1 cu. ft.-sec. falling 1 ft.

1.134 ft. water at 62 deg. F. = 1 in. Hg at 62 deg. F.

1,150.4 B. t. u. = Total heat sat. steam at atm. press.

11.52 lb. = theoret. air to burn 1 lb. carbon

12 = atomic wgt. carbon (C)

12.387 cu. ft. = vol. 1 lb. air at 32 deg. F. and 14.7 lb. per sq. in.

12.52 lb. = wgt. theoret. combustion products from 1 lb. C.

1,273,239* circular mils = 1 sq. in.

13.144 cu. ft. = vol. 1 lb. air at 62 deg. F. and 14.7 lb. per sq. in.

1.3410 hp. = 1 kw.

14 = atomic wgt. nitrogen (N)

1.406 = γ = ratio of C_p to C_v for air

1.4142* = square root of 2

14.223* lb. per sq. in. = 1 kg. per sq. cm. = 1 "metric atmosphere"

144* sq. in. = 1 sq. ft.

144 (143.15) B. t. u. = latent heat of fusion of ice.

14,600 B. t. u. per lb. = Cal. val. of carbon (C)

14.7 (14.696*) lb. per sq. in. = atm. press.

16* ounces = 1 lb.

16 = atomic wgt. oxygen (O)

0.1689 = C_v for air

0.017138* grams per liter = 1 grain per gal.

17.138* ppm. = 1 grain per gal.

1,728* cu. in. = 1 cu. ft.

1.7321* = square root of 3

1.8* B. t. u. per lb. = 1 kg. calorie per kg.

1.8* Fahrenheit degrees = 1 Centigrade degree

18 = mol. wgt. water (H_2O)

2,000* lb. = 1 short ton

2.0355 in. Hg at 32 deg. F. = 1 lb. per sq. in.

2.0416 in. Hg at 62 deg. F. = 1 lb. per sq. in.

2,116.3* lb. per sq. ft. = atm. press.

212* deg. F. = boiling point water at atm. press.

2.2046 lb.* = 1 kg.

223.8* × sq. root adiabatic heat drop = theoret. vel., ft. per sec., of steam expanding through nozzle.

2,240* lb. = long ton

2.3026* × $\log_{10} a = \log_e a$

2.309 ft. water at 62 deg. F. = 1 lb. per sq. in.

231* cu. in. = 1 gal.

0.2375 = C_p for air

(Continued on next page)

ENGINEERING CONSTANTS

(Continued from preceding page)

2.54* cm. = 1 in.
2,545 (2,547) B. t. u. per hr. = 1 hp.
2.666 lb. = wgt. oxygen required to burn 1 lb. carbon
27* cu. ft. = 1 cubic yard
−270 deg. C. = absolute zero
2.7183* = e = base hyperbolic logs.
27.71 in. water at 62 deg. F. = 1 lb. per sq. in.
277.274 cu. in. = 1 British gal.
28 = mol. wgt. nitrogen gas (N_2)
28 = mol. wgt. carbon monoxide (CO)
28.8 = equivalent mol. wgt. of air
288,000* B. t. u. per 24 hr. = 1 ton of refrigeration
29.921* in. Hg at 32 deg. F. = atm. press.
3* ft. = 1 yard
30 in. Hg at 62 deg. = atm. press. (very closely)
3.1416* = π (Greek letter "pi") = ratio circumference of circle to diameter = ratio area of circle to square of radius
32* deg. F. = freezing point of water = 0 deg. C.
32 = atomic wgt. sulphur (S)
32 = mol. wgt. oxygen gas (O_2)
32.5* gal. = 1 barrel
3.2808* ft. = 1 meter
33,000* ft.-lb. per min. = 1 hp.
33.947 ft. water at 62 deg. F. = atm. press.
3,415 B. t. u. = 1 kw.-hr.
3.45* lb. steam "f. & a. 212" per sq. ft. of heating surface per hr. = rated boiler evaporation.
34.56 lb. = wgt. air to burn 1 lb. hydrogen (H)
35.314* cu. ft. = 1 cu. meter
3.785* liters = 1 gal.
39.37* in. = 1 meter = 100 cm.
3.9683* B. t. u. = 1 kg. calorie
4,000 B. t. u. (4,050) = cal. val. of sulphur (S)
4.32 lb. = wgt. air req. to burn 1 lb. sulphur (S)
0.433 lb. per sq. in. = 1 ft. of water at 62 deg. F.
44 = mol. wgt. carbon dioxide (CO_2)
0.45359* kg. = 1 lb.
−460 (459.6) deg. F. = absolute zero.
0.47 B. t. u. per pound per deg. F. = approx. specific heat of super-heated steam at atm. press.
0.491 lb. per sq. in. = 1 in. Hg at 62 deg. F.
5.196 lb. per sq. ft. = 1 in. water at 62 deg. F.
5,280* ft. = 1 mile
53.32 = R, a constant for air, in expansion equation: $PV = MRT$
550* ft.-lb. per sec. = 1 hp.
57.296* deg. = 1 radian (angle)
58.349* grains per gal. = 1 gram per liter
59.76 lb. = wgt. 1 cu. ft. water at 212 deg. F.
61.023* cu. in. = 1 liter
62,000 B. t. u. = cal. val. (higher) hydrogen (H)
0.62137* miles = 1 kilometer
0.062428* lb. per cu. ft. = 1 kg. per cu. meter
62.5 (62.355) lb. = wgt. 1 cu. ft. water at 62 deg. F.
7,000* grains = 1 lb.
0.0735 in. Hg at 62 deg. F. = 1 in. water at 62 deg. F.
746 (745.7) watts = 1 hp.
7.5 (7.4805*) gal. = 1 cu. ft.
760* millimeters Hg = atm. press. at 0 deg. C.
0.07608 lb. = wgt. 1 cu. ft. air at 62 deg. F. and 14.7 lb. per sq. in.
778 (777.5) ft.-lb. = 1 B. t. u.
0.7854* (=3.1416 ÷ 4) × diameter squared = area circle
8 = lb. oxygen required to burn 1 lb. hydrogen (H)

ENGINEERING CONSTANTS

8.025* (= square root of 2 g) × square root of head (ft.) = theoretical velocity of fluids in ft. per sec.

0.08073 lb. = wgt. 1 cu. ft. air at 32 deg. and 14.7 lb. per sq. in.

8⅓ (8.3356) lb. = wgt. 1 gal. water at 62 deg. F.

8,760* hr. = 1 year of 365 days

88* ft. per sec. (min.) = 1 mile per min. (hr.)

9* sq. ft. = 1 sq. yard.

0.0929* sq. meters = 1 sq. ft.

970.4 B. t. u. = Latent heat of evap. of water at 212 deg. F.

ABBREVIATIONS AND SYMBOLS

α —Alpha
A or amp —ampere
Å —angstrom
a.c. —alternating current
A.F.S. —American Foundrymen's Society
Ag —silver
A.I.S.I. —American Iron and Steel Institute
Al —aluminum
alk. —alkaline
appr. —approximately
As —arsenic
A.S.A. —American Standards Association
A.S.M. —American Society for Metals
A.S.M.E. —American Society of Mechanical Engineers
A.S.T.M. —American Society for Testing Materials
av. (ave.) —average
B —(a) boron
 —(b) inductance
bbl. —barrel
bd. —board
B.H.N. —Brinell hardness number
Bi —bismuth
b.p. —boiling point
BTU —British thermal unit
C —(a) carbon
 —(b) Centigrade
Ca —calcium
cal. —calorie
cm. —centimeter
cgs —centimeter-gram-second system
Cl —chlorine
Co —cobalt
coef. —coefficient
conc. —concentrated
c.p. —candle power
Cr —chromium
cu. —cubic
Cu —copper
cu. ft. —cubic foot
cu. in. —cubic inch
δ —delta
db. —decibel
d.c. —direct current
deg. or ° —degree
dia[m.] —diameter
dil. —dilute
do. —ditto
E —electric pressure (volts)
e.g. —for example
el[ong.] —elongation
emf —electromotive force
etc. —and so forth
F, Fahr —Fahrenheit
fbm —board feet
Fe —iron
Fig. —figure
fpm —feet per minute
fps —(a) feet per second
 —(b) foot-pound-second system
FSG —first-stage graphitization
ft. —foot
γ —gamma
gal. —gallon
g. (or gm.) —gram
H —(a) hydrogen
 —(b) magnetic field intensity
 —(c) enthalpy
H_c —coercive force
He —helium
Hg —mercury
h.p. —horse power
hr. —hour
I —(a) iodine
 —(b) electric current (amps.)
 —(c) moment of inertia
ibid. —ibidem, in the same place
id. —the same
I.D. —inside diameter
i.e. —that is
in(s) —inch (es)
ips —inches per second
K —(a) potassium
 —(b) Kelvin temperature scale
 —(c) kilo (x 1,000)
k_t —thermal conductivity

ABBREVIATIONS AND SYMBOLS

k_f	—fatigue notch factor
kg or kgm	—kilogram(s)
kw.	—kilowatt
kX	—kilo-X unit (appr. 1 Å)
l	—liter
L	—(a) length (b) inductance
lb.	—pound
max.	—maximum
Md	—median
Mg	—magnesium
mi.	—mile
μ or mu	—micron
min.	—(a) minimum —(b) minute
MKS	—magnetic units in the cgs system (oersteds, gausses)
ml	—milliliter(s)
Mn	—manganese
mm	—millimeter
Mo	—molybdenum
m.p.	—melting point
N	—(a) nitrogen —(b) Number; total weight
Na	—sodium
NBS	—National Bureau of Standards
NDT	—nil ductility transition
O	—oxygen
O.D.	—outside diameter
op. cit.	—in the works quoted
oz.	—ounce
P	—(a) phosphorus —(b) probability
p.	—page
Pb	—lead
p.f.	—power factor
pL	—parting line
pp.	—pages
ppm	—parts per million
psi.	—pounds per square inch
Pt	—platinum

q.v.	—which see
r, R	—radius
R	—(a) resistance (elect.) —(b) resistivity (magnetic)
$R_{(\ )}$	—Rockwell hardness, scale in parenthesis
r.m.s.	—root mean square
r.p.m.	—revolutions per minute
S	—sulfur
"S" curve	—T-T-T curve
S.A.E.	—Society of Automotive Engineers
Se	—selenium
sec.	—second
seq.	—following
sfpm	—surface feet per minute
Si	—silicon
σ	—sigma; standard deviation
S-N	—stress—number of cycles
sp.	—specific
sq.	—square
SSG	—second-stage graphitization
std.	—standard
t, T	—temperature
Ta	—tantalum
Te	—tellurium
Ti	—titanium
T.S.	—tensile strength
T-T-T	—time-temperature-transformation
U.T.S.	—ultimate tensile strength
V	—(a) vanadium (b) volts
V. (or Vol.)	—volume
viz.	—namely
w	—watt
W	—tungsten (wolfram)
wt.	—weight
Y.Pt.	—yield point
yr.	—year
Y.S.	—yield strength
Zn	—zinc
Zr	—zirconium

WEIGHTS AND MEASURES

Linear Measure

12 inches = 1 foot
3 feet = 1 yard
1760 yards or 5280 feet = 1 mile
1000 mils = 1 inch
16½ feet or 5½ yards = 1 rod
(Sometimes called pole or perch.)

Square Measure

100 square feet = 1 square
(Used for roofing, etc.)
30¼ square yards = 1 square rod
160 square rods = 1 acre
640 acres = 1 square mile

Liquid Measure

4 gills = 1 pint
2 pints = 1 quart
4 quarts = 1 gallon
1 U. S. gallon = 231 cubic inches, 3.785 liters
1 British Imperial gallon = 277.41 cubic inches = 1.2 U. S. gallons
7.48 U. S. gallons = 1 cubic foot

Dry Measure — U. S.

2 pints = 1 quart
8 quarts = 1 peck
4 pecks = 1 bushel
1 Standard U. S. bushel = 2,150.42 cubic inches = 1.2445 cubic feet
1 British Imperial bushel = 2,218.19 cubic inches = 1.2837 cubic feet

Board Measure

One board foot is a piece of wood 12 inches square by 1 inch thick, or 144 cubic inches. 1 cubic foot, therefore, equals 12 board feet.

Shipping Measure

Register ton is used to measure internal capacity of ships. 100 cubic feet = 1 register ton.

Shipping ton, for measurement of cargo:

$$40 \text{ cubic feet} = \begin{cases} \text{1 U. S. shipping ton} \\ \text{32.143 U. S. bushels} \\ \text{31.16 Imperial bushels} \end{cases}$$

$$42 \text{ cubic feet} = \begin{cases} \text{1 British shipping ton} \\ \text{33.75 U. S. bushels} \\ \text{32.718 Imperial bushels} \end{cases}$$

Measures of Weight — Avoirdupois

16 drachms or 437.5 grains = 1 ounce (oz.)
16 ounces or 7000 grains = 1 pound (lb.)
2000 pounds = 1 net or short ton
2240 pounds = 1 gross or long ton
2204.6 pounds = 1 metric ton

Specific Gravity

The specific gravity of a substance is its weight as compared with the weight of an equal bulk of pure water.

For making specific gravity determinations the temperature of the water is usually taken at 62 degrees Fahrenheit when 1 cubic foot of water weighs 62.355 pounds. Water is at its greatest density at 39.2 degrees Fahrenheit or 4 degrees Centigrade.

Temperature

The following equation will be found convenient for transforming temperature from one system to another:

Let F = degrees Fahrenheit; C = degrees Centigrade; R = degrees Réaumur.

$$\frac{F-32}{180} = \frac{C}{100} = \frac{R}{80}$$

WEIGHTS AND MEASURES

Linear Measure

French		U. S. and British
1 meter	=	39.37 inches or 3.28083 feet or 1.09361 yards
0.3048 meter	=	1 foot
1 centimeter	=	0.3937 inch
2.54 centimeters	=	1 inch
25.4 millimeters	=	1 inch
1 kilometer	=	1093.61 yards or 0.62137 mile

Square Measure

French		U. S. and British
1 square meter	=	10.764 square feet or 1.196 square yards
0.836 square meter	=	1 square yard
6.452 square centimeters	=	1 square inch
1 square millimeter	=	0.00155 square inch = 1973.5 circular mils
645.2 square millimeters	=	1 square inch
1 centiare = 1 square meter	=	10.764 square feet
1 are = 1 square decameter	=	1076.41 square feet
1 hectare = 100 ares	=	107641. square feet 2.471 acres
1 square kilometer	=	0.3861 square miles 247.1 acres

Volume

French		U. S. and British
1 cubic meter	=	35.314 cubic feet or 1.308 cubic yards
0.7646 cubic meter	=	1 cubic yard
0.02832 cubic meter	=	1 cubic foot
1 cubic decimeter	=	61.023 cubic inches or 0.0353 cubic foot
16.387 cubic centimeters	=	1 cubic inch
1 litre = 1 cubic decimeter	=	61.023 cubic inch = 1.05671 quarts (U. S.)
1 hectolitre or decistere	=	3.5314 cubic feet = 2.8375 bushels (U. S.)
1 stere, kilolitre, or cubic meter	=	1.308 cubic yards = 28.37 bushels (U. S.)

Weight

1 gram is the weight of 1 cubic centimeter of water at 4 degrees Centigrade.

French		U. S. and British
1 gram	=	15.432 grains
0.0648 gram	=	1 grain
28.35 gram	=	1 ounce avoirdupois
1 kilogram	=	2.2046 pounds
0.4536 kilogram	=	1 pound
1 tonne or metric ton or 1000 kilogram	=	0.9842 long tons 19.68 hundredweights (cwt.) 2204.6 pounds
1.016 metric tons 1016 kilograms	=	1 long ton of 2240 pounds

The metric system has in recent years been adopted as standard in engineering and technological work in China and the U.S.S.R.

ENGINEERING CONVERSION FACTORS

Multiply	by*	to obtain
Acres	.404687	hectares
"	4.04687×10^{-3}	square kilometers
Ares	1076.39	square feet
board feet	144 sq. in. × 1 in.	cubic inches
" "	.0833	cubic feet
centimeters	3.28083×10^{-2}	feet
"	.3937	inches
cubic centimeters	3.53145×10^{-5}	cubic feet
" "	6.102×10^{-2}	cubic inches
cubic feet	2.8317×10^{4}	cubic centimeters
" "	2.8317×10^{-2}	cubic meters
" "	6.22905	gallons, British Imperial
" "	28.3170	liters
" "	2.38095×10^{-2}	tons, British Shipping
" "	.025	tons, U. S. Shipping
cubic inches	16.38716	cubic centimeters
cubic meters	35.3145	cubic feet
" "	1.30794	cubic yards
cubic yards	.764559	cubic meters
degrees, angular	.0174533	radians
degrees, Fahrenheit (less 32 F.)	.5556	degrees, Centigrade
" Centigrade	1.8	degrees, Fahrenheit (less 32 F.)
foot pounds	.13826	kilogram meters
feet	30.4801	centimeters
"	.304801	meters
"	304.801	millimeters
"	1.64468×10^{-4}	miles, nautical
gallons, British Imperial	.160538	cubic feet
" " "	1.20091	gallons, U. S.
" " "	4.54596	liters
gallons, U. S.	.832702	gallons, British Imperial
" "	.13368	cubic feet
" "	231.	cubic inches
" "	3.78543	liters
grams, metric	2.20462×10^{-3}	pounds, avoirdupois
hectares	2.47104	acres
"	1.076387×10^{-5}	square feet
"	3.86101×10^{-3}	square miles
horse-power, metric	.98632	horse-power, U. S.
horse-power, U. S.	1.01387	horse-power, metric
inches	2.54001	centimeters
"	2.54001×10^{-2}	meters
"	25.4001	millimeters
kilograms	2.20462	pounds
"	9.84206×10^{-4}	long tons
"	1.10231×10^{-3}	short tons
kilogram meters	7.233	foot pounds
kilograms per meter	.671972	pounds per foot
kilograms per square centimeter	14.2234	pounds per square inch
kilograms per square meter	.204817	pounds per square foot
" " " "	9.14362×10^{-5}	long tons per square foot
kilograms per square millimeter	1422.34	pounds per square inch
" " " "	.634973	long tons per square inch
kilograms per cubic meter	6.24283×10^{-2}	pounds per cubic foot
kilometers	.62137	miles, statute
"	.53959	miles, nautical

* The expressions $\times 10^{-2}$, $\times 10^{-3}$, $\times 10^{-4}$, $\times 10^{-5}$, and $\times 10^{-6}$, following certain multipliers, indicate that the decimal point in the product — of left-column value times multiplier — is to be moved respectively 2, 3, 4, 5, or 6 places to the left.

ENGINEERING CONVERSION FACTORS

Multiply	by*	to obtain
liters	.219975	gallons, British Imperial
"	.26417	gallons, U. S.
"	3.53145×10^{-2}	cubic feet
meters	3.28083	feet
"	39.37	inches
"	1.09361	yards
miles, statute	1.60935	kilometers
" "	.8684	miles, nautical
miles, nautical	6080.204	feet
" "	1.85325	kilometers
" "	1.1516	miles, statute
millimeters	3.28083×10^{-3}	feet
"	3.937×10^{-2}	inches
pounds, avoirdupois	453.592	grams, metric
" "	.453592	kilograms
" "	4.464×10^{-4}	tons, long
" "	4.53592×10^{-4}	tons, metric
pounds per foot	1.48816	kilograms per meter
pounds per square foot	4.88241	kilograms per square meter
pounds per square inch	7.031×10^{-2}	kilograms per square centimeter
" " " "	7.031×10^{-4}	kilograms per square millimeter
pounds per cubic foot	16.0184	kilograms per cubic meter
radians	57.29578	degrees, angular
square centimeters	.1550	square inches
square feet	9.29034×10^{-4}	ares
" "	9.29034×10^{-6}	hectares
" "	.0929034	square meters
square inches	6.45163	square centimeters
" "	645.163	square millimeters
square kilometers	247.104	acres
" "	.3861	square miles
square meters	10.7639	square feet
" "	1.19599	square yards
square miles	259.0	hectares
" "	2.590	square kilometers
square millimeters	1.550×10^{-3}	square inches
square yards	.83613	square meters
tons, long	1016.05	kilograms
" "	2240.	pounds
" "	1.01605	tons, metric
" "	1.120	tons, short
tons, long, per square foot	1.09366×10^{4}	kilograms per square meter
tons, long, per square inch	1.57494	kilograms per square millimeter
tons, metric	2204.62	pounds
" "	.98421	tons, long
" "	1.10231	tons, short
tons, short	907.185	kilograms
" "	.892857	tons, long
" "	.907185	tons, metric
tons, British Shipping	42.00	cubic feet
" " "	1.050	tons, U. S. Shipping
tons, U. S. Shipping	40.00	cubic feet
" " "	.952381	tons, British Shipping
yards	.914402	meters

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* The expressions $\times 10^{-2}$, $\times 10^{-3}$, $\times 10^{-4}$, $\times 10^{-5}$, and $\times 10^{-6}$, following certain multipliers, indicate that the decimal point in the product – of left-column value times multiplier – is to be moved respectively 2, 3, 4, 5, or 6 places to the left.

CONVERSION OF INCH FRACTIONS INTO MILLIMETERS

(From 1/32 of an inch to one foot)

Inches	0	1	2	3	4	5
....	....	25.4	50.8	76.2	101.6	127.0
1/32	0.79	26.2	51.6	77.0	102.4	127.8
1/16	1.59	27.0	52.4	77.8	103.2	128.6
3/32	2.38	27.8	53.2	78.6	104.0	129.4
1/8	3.18	28.6	54.0	79.4	104.8	130.2
5/32	3.97	29.4	54.8	80.2	105.6	131.0
3/16	4.76	30.2	55.6	81.0	106.4	131.8
7/32	5.56	31.0	56.4	81.8	107.2	132.6
1/4	6.35	31.8	57.2	82.6	108.0	133.4
9/32	7.14	32.5	57.9	83.3	108.7	134.1
5/16	7.94	33.3	58.7	84.1	109.5	134.9
11/32	8.73	34.1	59.5	84.9	110.3	135.7
3/8	9.53	34.9	60.3	85.7	111.1	136.5
13/32	10.32	35.7	61.1	86.5	111.9	137.3
7/16	11.11	36.5	61.9	87.3	112.7	138.1
15/32	11.91	37.3	62.7	88.1	113.5	138.9
1/2	12.70	38.1	63.5	88.9	114.3	139.7
17/32	13.49	38.9	64.3	89.7	115.1	140.5
9/16	14.29	39.7	65.1	90.5	115.9	141.3
19/32	15.08	40.5	65.9	91.3	116.7	142.1
5/8	15.88	41.3	66.7	92.1	117.5	142.9
21/32	16.67	42.1	67.5	92.9	118.3	143.7
11/16	17.46	42.9	68.3	93.7	119.1	144.5
23/32	18.26	43.7	69.1	94.5	119.9	145.3
3/4	19.05	44.5	69.9	95.3	120.7	146.1
25/32	19.84	45.2	70.6	96.0	121.4	146.8
13/16	20.64	46.0	71.4	96.8	122.2	147.6
27/32	21.43	46.8	72.2	97.6	123.0	148.4
7/8	22.23	47.6	73.0	98.4	123.8	149.2
29/32	23.02	48.4	73.8	99.2	124.6	150.0
15/16	23.81	49.2	74.6	100.0	125.4	150.8
31/32	24.61	50.0	75.4	100.8	126.2	151.6

Example—$10\frac{7}{32}$ inch = 259.6 mm. Tenths of millimeters are amply sufficient for all practical purposes.

CONVERSION OF INCH FRACTIONS INTO MILLIMETERS

(From 1/32 of an inch to one foot)

Inches	6	7	8	9	10	11
....	152.4	177.8	203.2	228.6	254.0	279.4
1/32	153.2	178.6	204.0	229.4	254.8	280.2
1/16	154.0	179.4	204.8	230.2	255.6	281.0
3/32	154.8	180.2	205.6	231.0	256.4	281.8
1/8	155.6	181.0	206.4	231.8	257.2	282.6
5/32	156.4	181.8	207.2	232.6	258.0	283.4
3/16	157.2	182.6	208.0	233.4	258.8	284.2
7/32	158.0	183.4	208.8	234.2	259.6	285.0
1/4	158.8	184.2	209.6	235.0	260.4	285.8
9/32	159.5	184.9	210.3	235.7	261.1	286.5
5/16	160.3	185.7	211.1	236.5	261.9	287.3
11/32	161.1	186.5	211.9	237.3	262.7	288.1
3/8	161.9	187.3	212.7	238.1	263.5	288.9
13/32	162.7	188.1	213.5	238.9	264.3	289.7
7/16	163.5	188.9	214.3	239.7	265.1	290.5
15/32	164.3	189.7	215.1	240.5	265.9	291.3
1/2	165.1	190.5	215.9	241.3	266.7	292.1
17/32	165.9	191.3	216.7	242.1	267.5	292.9
9/16	166.7	192.1	217.5	242.9	268.3	293.7
19/32	167.5	192.9	218.3	243.7	269.1	294.5
5/8	168.3	193.7	219.1	244.5	269.9	295.3
21/32	169.1	194.5	219.9	245.3	270.7	296.1
11/16	169.9	195.3	220.7	246.1	271.5	296.9
23/32	170.7	196.1	221.5	246.9	272.3	297.7
3/4	171.5	196.9	222.3	247.7	273.1	298.5
25/32	172.2	197.6	223.0	248.4	273.8	299.2
13/16	173.0	198.4	223.8	249.2	274.6	300.0
27/32	173.8	199.2	224.6	250.0	275.4	300.8
7/8	174.6	200.0	225.4	250.8	276.2	301.6
29/32	175.4	200.8	226.2	251.6	277.0	302.4
15/16	176.2	201.6	227.0	252.4	277.8	303.2
31/32	177.0	202.4	227.8	253.2	278.6	304.0

Example—$10\frac{7}{32}$ inch = 259.6 mm. Tenths of millimeters are amply sufficient for all practical pusposes.

DECIMAL EQUIVALENTS
INCH-MILLIMETER CONVERSION TABLE

½	¼	⅛	1/16	1/32	1/64	Decimals	Millimeters
					1	.015625	.396875
				1		.031250	.793750
					3	.046875	1.190625
			1			.062500	1.587500
					5	.078125	1.984375
				3		.093750	2.381250
					7	.109375	2.778125
		1				.125000	3.175000
					9	.140625	3.571875
				5		.156250	3.968750
					11	.171875	4.365625
			3			.187500	4.762500
					13	.203125	5.159375
				7		.218750	5.556250
					15	.234375	5.953125
	1					.250000	6.350000
					17	.265625	6.746875
				9		.281250	7.143750
					19	.296875	7.540625
			5			.312500	7.937500
					21	.328125	8.334375
				11		.343750	8.731250
					23	.359375	9.128125
		3				.375000	9.525000
					25	.390625	9.921875
				13		.406250	10.318750
					27	.421875	10.715625
			7			.437500	11.112500
					29	.453125	11.509375
				15		.468750	11.906250
					31	.484375	12.303125
1						.500000	12.700000
					33	.515625	13.096875
				17		.531250	13.493750
					35	.546875	13.890625
			9			.562500	14.287500
					37	.578125	14.684375
				19		.593750	15.081250
					39	.609375	15.478125
		5				.625000	15.875000
					41	.640625	16.271875
				21		.656250	16.668750
					43	.671875	17.065625
			11			.687500	17.462500
					45	.703125	17.859375
				23		.718750	18.256250
					47	.734375	18.653125
	3					.750000	19.050000
					49	.765625	19.446875
				25		.781250	19.843750
					51	.796875	20.240625
			13			.812500	20.637500
					53	.828125	21.034375
				27		.843750	21.431250
					55	.859375	21.828125
		7				.875000	22.225000
					57	.890625	22.621875
				29		.906250	23.018750
					59	.921875	23.415625
			15			.937500	23.812500
					61	.953125	24.209375
				31		.968750	24.606250
					63	.984375	25.003125
2	4	8	16	32	64	1.000000	25.400000

PRESSURE EQUIVALENTS

Ounces per Sq. In.	Lbs. per Sq. In.	Inches of Water	Inches of Mercury
0.25	0.016	0.433	0.0319
0.50	0.031	0.866	0.0638
1	0.062	1.732	0.1275
2	0.125	3.464	0.2551
3	0.187	5.196	0.3826
4	0.250	6.928	0.5102
5	0.312	8.660	0.6377
6	0.375	10.392	0.7653
7	0.437	12.124	0.8928
8	0.500	13.856	1.020
9	0.562	15.588	1.148
10	0.625	17.320	1.275
11	0.687	19.052	1.403
12	0.750	20.784	1.531
13	0.812	22.516	1.658
14	0.875	24.248	1.786
15	0.937	25.980	1.913
16	1.000	27.712	2.041
17	1.062	29.444	2.169
18	1.125	31.176	2.296
19	1.187	32.908	2.424
20	1.250	34.640	2.551
21	1.312	36.372	2.679
22	1.375	38.104	2.806
23	1.437	39.836	2.934
24	1.500	41.568	3.061
25	1.562	43.300	3.189
26	1.625	45.032	3.317
27	1.687	46.764	3.444
28	1.750	48.496	3.572
29	1.812	50.228	3.699
30	1.875	51.960	3.827
31	1.937	53.692	3.954
32	2.000	55.424	4.082
33	2.062	57.156	4.210
34	2.125	58.888	4.337
35	2.187	60.620	4.465

TEMPERATURE CONVERSION TABLES

General formula: °F. = (°C. × 9/5) + 32; °C. = (°F. − 32) × 5/9

C.		F.	C.		F.	C.		F.	C.		F.
−273.1	**−459.4**		−17.8	**0**	32	10.0	**50**	122.0	38	**100**	212
−268	**−450**		−17.2	**1**	33.8	10.6	**51**	123.8	43	**110**	230
−262	**−440**		−16.7	**2**	35.6	11.1	**52**	125.6	49	**120**	248
−257	**−430**		−16.1	**3**	37.4	11.7	**53**	127.4	54	**130**	266
−251	**−420**		−15.6	**4**	39.2	12.2	**54**	129.2	60	**140**	284
−246	**−410**		−15.0	**5**	41.0	12.8	**55**	131.0	66	**150**	302
−240	**−400**		−14.4	**6**	42.8	13.3	**56**	132.8	71	**160**	320
−234	**−390**		−13.9	**7**	44.6	13.9	**57**	134.6	77	**170**	338
−229	**−380**		−13.3	**8**	46.4	14.4	**58**	136.4	82	**180**	356
−223	**−370**		−12.8	**9**	48.2	15.0	**59**	138.2	88	**190**	374
−218	**−360**		−12.2	**10**	50.0	15.6	**60**	140.0	93	**200**	392
−212	**−350**		−11.7	**11**	51.8	16.1	**61**	141.8	99	**210**	410
−207	**−340**		−11.1	**12**	53.6	16.7	**62**	143.6	100	**212**	413
−201	**−330**		−10.6	**13**	55.4	17.2	**63**	145.4	104	**220**	428
−196	**−320**		−10.0	**14**	57.2	17.8	**64**	147.2	110	**230**	446
−190	**−310**		− 9.44	**15**	59.0	18.3	**65**	149.0	116	**240**	464
−184	**−300**		− 8.89	**16**	60.8	18.9	**66**	150.8	121	**250**	482
−179	**−290**		− 8.33	**17**	62.6	19.4	**67**	152.6	127	**260**	500
−173	**−280**		− 7.78	**18**	64.4	20.0	**68**	154.4	132	**270**	518
−169	**−273**	−459.4	− 7.22	**19**	66.2	20.6	**69**	156.2	138	**280**	536
−168	**−270**	−454	− 6.67	**20**	68.0	21.1	**70**	158.0	143	**290**	554
−162	**−260**	−436	− 6.11	**21**	69.8	21.7	**71**	159.8	149	**300**	572
−157	**−250**	−418	− 5.56	**22**	71.6	22.2	**72**	161.6	154	**310**	590
−151	**−240**	−400	− 5.00	**23**	73.4	22.8	**73**	163.4	160	**320**	608
−146	**−230**	−382	− 4.44	**24**	75.2	23.3	**74**	165.2	166	**330**	626
−140	**−220**	−364	− 3.89	**25**	77.0	23.9	**75**	167.0	171	**340**	644
−134	**−210**	−346	− 3.33	**26**	78.8	24.4	**76**	168.8	177	**350**	662
−129	**−200**	−328	− 2.78	**27**	80.6	25.0	**77**	170.6	182	**360**	680
−123	**−190**	−310	− 2.22	**28**	82.4	25.6	**78**	172.4	188	**370**	698
−118	**−180**	−292	− 1.67	**29**	84.2	26.1	**79**	174.2	193	**380**	716
−112	**−170**	−274	− 1.11	**30**	86.0	26.7	**80**	176.0	199	**390**	734
−107	**−160**	−256	− 0.56	**31**	87.8	27.2	**81**	177.8	204	**400**	752
−101	**−150**	−238	0	**32**	89.6	27.8	**82**	179.6	210	**410**	770
− 95.6	**−140**	−220	0.56	**33**	91.4	28.3	**83**	181.4	216	**420**	788
− 90.0	**−130**	−202	1.11	**34**	93.2	28.9	**84**	183.2	221	**430**	806
− 84.4	**−120**	−184	1.67	**35**	95.0	29.4	**85**	185.0	227	**440**	824
− 78.9	**−110**	−166	2.22	**36**	96.8	30.0	**86**	186.8	232	**450**	842
− 73.3	**−100**	−148	2.78	**37**	98.6	30.6	**87**	188.6	238	**460**	860
− 67.8	**− 90**	−130	3.33	**38**	100.4	31.1	**88**	190.4	243	**470**	878
− 62.2	**− 80**	−112	3.89	**39**	102.2	31.7	**89**	192.2	249	**480**	896
− 56.7	**− 70**	− 94	4.44	**40**	104.0	32.2	**90**	194.0	254	**490**	914
− 51.1	**− 60**	− 76	5.00	**41**	105.8	32.8	**91**	195.8			
− 45.6	**− 50**	− 58	5.56	**42**	107.6	33.3	**92**	197.6			
− 40.0	**− 40**	− 40	6.11	**43**	109.4	33.9	**93**	199.4			
− 34.4	**− 30**	− 22	6.67	**44**	111.2	34.4	**94**	201.2			
− 28.9	**− 20**	− 4	7.22	**45**	113.0	35.0	**95**	203.0			
− 23.3	**− 10**	14	7.78	**46**	114.8	35.6	**96**	204.8			
− 17.8	**− 0**	32	8.33	**47**	116.6	36.1	**97**	206.6			
			8.89	**48**	118.4	36.7	**98**	208.4			
			9.44	**49**	120.2	37.2	**99**	210.2			
						37.8	**100**	212.0			

Note:—The numbers in bold-face type refer to the temperature (in either centigrade or Fahrenheit degrees) which it is desired to convert into the other scale. If converting from Fahrenheit degrees to centigrade degrrees the equivalent temperature is in the left column, while if converting from degrees centigrade to degrees Fahrenheit, the equivalent temperature is in the column on the right.

TEMPERATURE CONVERSION TABLES

General formula: °F. = (°C. × 9/5) + 32; °C. = (°F. − 32) × 5/9

C.		F.	C.		F.	C.		F.	C.		F.	C.		F.
260	**500**	932	538	**1000**	1832	816	**1500**	2732	1093	**2000**	3632	1371	**2500**	4532
266	**510**	950	543	**1010**	1850	821	**1510**	2750	1099	**2010**	3650	1377	**2510**	4550
271	**520**	968	549	**1020**	1868	827	**1520**	2768	1104	**2020**	3668	1382	**2520**	4568
277	**530**	986	554	**1030**	1886	832	**1530**	2786	1110	**2030**	3686	1388	**2530**	4586
282	**540**	1004	560	**1040**	1904	838	**1540**	2804	1116	**2040**	3704	1393	**2540**	4604
288	**550**	1022	566	**1050**	1922	843	**1550**	2822	1121	**2050**	3722	1399	**2550**	4622
293	**560**	1040	571	**1060**	1940	849	**1560**	2840	1127	**2060**	3740	1404	**2560**	4640
299	**570**	1058	577	**1070**	1958	854	**1570**	2858	1132	**2070**	3758	1410	**2570**	4658
304	**580**	1076	582	**1080**	1976	860	**1580**	2876	1138	**2080**	3776	1416	**2580**	4676
310	**590**	1094	588	**1090**	1994	866	**1590**	2894	1143	**2090**	3794	1421	**2590**	4694
316	**600**	1112	593	**1100**	2012	871	**1600**	2912	1149	**2100**	3812	1427	**2600**	4712
321	**610**	1130	599	**1110**	2030	877	**1610**	2930	1154	**2110**	3830	1432	**2610**	4730
327	**620**	1148	604	**1120**	2048	882	**1620**	2948	1160	**2120**	3848	1438	**2620**	4748
332	**630**	1166	610	**1130**	2066	888	**1630**	2966	1166	**2130**	3866	1443	**2630**	4766
338	**640**	1184	616	**1140**	2084	893	**1640**	2984	1171	**2140**	3884	1449	**2640**	4784
343	**650**	1202	621	**1150**	2102	899	**1650**	3002	1177	**2150**	3902	1454	**2650**	4802
349	**660**	1220	627	**1160**	2120	904	**1660**	3020	1182	**2160**	3920	1460	**2660**	4820
354	**670**	1238	632	**1170**	2138	910	**1670**	3038	1188	**2170**	3938	1466	**2670**	4838
360	**680**	1256	638	**1180**	2156	916	**1680**	3056	1193	**2180**	3956	1471	**2680**	4856
366	**690**	1274	643	**1190**	2174	921	**1690**	3074	1199	**2190**	3974	1477	**2690**	4874
371	**700**	1292	649	**1200**	2192	927	**1700**	3092	1204	**2200**	3992	1482	**2700**	4892
377	**710**	1310	654	**1210**	2210	932	**1710**	3110	1210	**2210**	4010	1488	**2710**	4910
382	**720**	1328	660	**1220**	2228	938	**1720**	3128	1216	**2220**	4028	1493	**2720**	4928
388	**730**	1346	666	**1230**	2246	943	**1730**	3146	1221	**2230**	4046	1499	**2730**	4946
393	**740**	1364	671	**1240**	2264	949	**1740**	3164	1227	**2240**	4064	1504	**2740**	4964
399	**750**	1382	677	**1250**	2282	954	**1750**	3182	1232	**2250**	4082	1510	**2750**	4982
404	**760**	1400	682	**1260**	2300	960	**1760**	3200	1238	**2260**	4100	1516	**2760**	5000
410	**770**	1418	688	**1270**	2318	966	**1770**	3218	1243	**2270**	4118	1521	**2770**	5018
416	**780**	1436	693	**1280**	2236	971	**1780**	3236	1249	**2280**	4136	1527	**2780**	5036
421	**790**	1454	699	**1290**	2354	977	**1790**	3254	1254	**2290**	4154	1532	**2790**	5054
427	**800**	1472	704	**1300**	2372	982	**1800**	3272	1260	**2300**	4172	1538	**2800**	5072
432	**810**	1490	710	**1310**	2390	988	**1810**	3290	1266	**2310**	4190	1543	**2810**	5090
438	**820**	1508	716	**1320**	2408	993	**1820**	3308	1271	**2320**	4208	1549	**2820**	5108
443	**830**	1526	721	**1330**	2426	999	**1830**	3326	1277	**2330**	4226	1554	**2830**	5126
449	**840**	1544	727	**1340**	2444	1004	**1840**	3344	1282	**2340**	4244	1560	**2840**	5144
454	**850**	1562	732	**1350**	2462	1010	**1850**	3362	1288	**2350**	4262	1566	**2850**	5162
460	**860**	1580	738	**1360**	2480	1016	**1860**	3380	1293	**2360**	4280	1571	**2860**	5180
466	**870**	1598	743	**1370**	2498	1021	**1870**	3398	1299	**2370**	4298	1577	**2870**	5198
471	**880**	1616	749	**1380**	2516	1027	**1880**	3416	1304	**2380**	4316	1582	**2880**	5216
477	**890**	1634	754	**1390**	2534	1032	**1890**	3434	1310	**2390**	4334	1588	**2890**	5234
482	**900**	1652	760	**1400**	2552	1038	**1900**	3452	1316	**2400**	4352	1593	**2900**	5252
488	**910**	1670	766	**1410**	2570	1043	**1910**	3470	1321	**2410**	4370	1599	**2910**	5270
493	**920**	1688	771	**1420**	2588	1049	**1920**	3488	1327	**2420**	4388	1604	**2920**	5288
499	**930**	1706	777	**1430**	2606	1054	**1930**	3506	1332	**2430**	4406	1610	**2930**	5306
504	**940**	1724	782	**1440**	2624	1060	**1940**	3524	1338	**2440**	4424	1616	**2940**	5324
510	**950**	1742	788	**1450**	2642	1066	**1950**	3542	1343	**2450**	4442	1621	**2950**	5342
516	**960**	1760	793	**1460**	2660	1071	**1960**	3560	1349	**2460**	4460	1627	**2960**	5360
521	**970**	1778	799	**1470**	2678	1077	**1970**	3578	1354	**2470**	4478	1632	**2970**	5378
527	**980**	1796	804	**1480**	2696	1082	**1980**	3596	1360	**2480**	4496	1638	**2980**	5396
532	**990**	1814	810	**1490**	2714	1088	**1990**	3614	1366	**2490**	4514	1643	**2990**	5414
						1093	**2000**	3632				1649	**3000**	5432

INTERPOLATION FACTORS

C.		F.	C.		F.	C.		F.	C.		F.	C.		F.
0.56	**1**	1.8	1.67	**3**	5.4	2.78	**5**	9.0	3.89	**7**	12.6	5.00	**9**	16.2
1.11	**2**	3.6	2.22	**4**	7.2	3.33	**6**	10.8	4.44	**8**	14.4	5.56	**10**	18.0

COMPARATIVE VALUES OF FUELS

The use or consumption of fuels in foundry operations—gray iron, steel, malleable and nonferrous—is of increasing importance to management because of advancing costs on both a primary or "as produced" basis and "delivered "basis.

It has been argued in the past by proponents of liquid and gaseous fuels that these are burned at higher thermal efficiency than coal, but there is ample proof to the contrary today except when coal is burned on grates for which there is no excuse with pulverizing equipment of the unit or direct firing type available for furnace, oven and boiler firing.

HEAT UNITS PER DOLLAR

COAL

B. T. U. Per Lb. COAL	Ton Price:	$4.00	$6.00	$8.00	$10.00	$12.00	$14.00	$16.00
7,000	B. T. U. Per $	3,500,000	2,333,000	1,750,000	1,400,000	1,166,000	1,000,000	875,000
8,000		4,000,000	2,667,000	2,000,000	1,600,000	1,333,000	1,143,000	1,000,000
9,000		4,500,000	3,000,000	2,250,000	1,800,000	1,500,000	1,286,000	1,125,000
10,000		5,000,000	3,333,000	2,500,000	2,000,000	1,666,000	1,429,000	1,250,000
11,000		5,500,000	3,667,000	2,750,000	2,200,000	1,833,000	1,571,000	1,375,000
12,000		6,000,000	4,000,000	3,000,000	2,400,000	2,000,000	1,714,000	1,500,000
13,000		6,500,000	4,333,000	3,250,000	2,600,000	2,166,000	1,857,000	1,625,000
14,000		7,000,000	4,667,000	3,500,000	2,800,000	2,333,000	2,000,000	1,750,000
15,000		7,500,000	5,000,000	3,750,000	3,000,000	2,500,000	2,143,000	1,875,000

GAS

B. T. U. Per Cu Ft. GAS	Price Per 1,000 Cu. Ft.:	$0.30	$0.40	$0.50	$0.60	$0.70	$0.80	$0.90
200	B. T. U. Per $	670,000	500,000	400,000	333,000	285,000	250,000	222,000
400		1,330,000	1,000,000	800,000	667,000	570,000	500,000	444,000
*550		1,815,000	1,375,000	1,100,000	917,000	786,000	689,000	622,000
600		2,000,000	1,500,000	1,200,000	1,000,000	857,000	750,000	666,000
800		2,670,000	2,000,000	1,600,000	1,333,000	1,140,000	1,000,000	888,000
1,000		3,330,000	2,500,000	2,000,000	1,667,000	1,430,000	1,250,000	1,110,000

*—Denotes Municipal Gas.

HEAT UNITS PER DOLLAR

OIL

A.P.I.	Std. Baume Gravity	Specific Gravity	Lbs. Per Gal.	B.T.U. Per Gal.	Gal. Price	$0.04	$0.05	$0.06	$0.07	$0.08
No. 1	40°-42°	.8203	6.834	136,640	B.t.u. per $	3,416,000	2,733,000	2,277,000	1,952,000	1,708,000
No. 2	32°-36°	.8550	7.123	139,380		3,485,000	2,788,000	2,323,000	1,991,000	1,742,000
No. 3	28°-32°	.8762	7.300	141,700		3,543,000	2,834,000	2,362,000	2,024,000	1,771,000
No. 4	24°-26°	.9042	7.533	144,800		3,620,000	2,896,000	2,413,000	2,069,000	1,810,000
No. 5	16°-20°	.9465	7.855	149,420		3,736,000	2,988,000	2,490,000	2,135,000	1,868,000

A.P.I.	Std. Baume Gravity	Specific Gravity	Lbs. Per Gal.	B.T.U. Per Gal.	Gal. Price:	$0.09	$0.10	$0.11	$0.12	$0.13
No. 1	40°-42°	.8203	6.834	136,640	B.t.u. per $	1,518,000	1,366,000	1,242,000	1,139,000	1,051,000
No. 2	32°-36°	.8550	7.123	139,380		1,549,000	1,394,000	1,267,000	1,162,000	1,072,000
No. 3	28°-32°	.8762	7.300	141,700		1,574,000	1,417,000	1,288,000	1,181,000	1,090,000
No. 4	24°-26°	.9042	7.533	144,800		1,609,000	1,448,000	1,316,000	1,207,000	1,114,000
No. 5	16°-20°	.9465	7.885	149,420		1,660,000	1,494,000	1,358,000	1,245,000	1,149,000

ELECTRICITY

B.T.U. Per K.W.H.	Price Per K.W.H.							
	K.W.H. Price:	$0.0075	$0.01	$0.0125	$0.015	$0.02	$0.025	$0.03
3415	B.T.U. Per $	455,000	341,500	273,000	228,000	170,000	137,000	114,000

EXAMPLES:
Using 14,000 B.t.u. Coal at $10.00 per ton, $1.00 purchases 2,800,000 B.t.u.'s
Using 550 B.t.u. Gas at 50c per M. $1.00 purchases 1,100,000 B.t.u.'s
Using 1,000 B.t.u. Gas at 40c per M. $1.00 purchases 2,500,000 B.t.u.'s
Using No. 3 Grade Oil at 5c per Gal. $1.00 purchases 2,834,000 B.t.u.'s
Using Electricity at 1c per K.W.H. $1.00 purchases 341,500 B.t.u.'s

NOTE:—Efficiencies, handling, maintenance and power to operate must be calculated in arriving at the net B.t.u. purchased with each fuel.

THE AIR REQUIREMENTS FOR COMBUSTION*

(60° F Temp. and 29.92 Inches of Mercury)

Effluent Gases			Fraction of 1 Lb. Carbon Burned to		Air Requirements Lbs. per 1 Lb. Carbon			Gases Produced Lbs. per Lb. Carbon				Heat Developed BTU. per Lb. Carbon			Efficiency of Combustion %	Lbs. / Lb. C.	Cu. Ft. / Lb. C.
CO_2 %	CO %	N_2 %	A CO_2	B CO	O_2	N_2	Air	CO_2	CO	N_2	Total	CO_2	CO	Total			
0	34.7	65.3	0.000	1.000	1.33	4.44	5.77	0.00	2.33	4.44	6.77	000	4350	4350	29.9	5.77	75.4
1	33.0	66.0	0.029	0.971	1.37	4.57	5.94	0.11	2.26	4.57	6.94	422	4224	4646	31.9	5.94	77.7
2	31.4	66.6	0.060	0.940	1.41	4.70	6.11	0.22	2.19	4.70	7.11	873	4089	4962	34.1	6.11	79.9
3	29.7	67.3	0.092	0.908	1.45	4.85	6.30	0.34	2.11	4.85	7.30	1338	3950	5288	36.3	6.30	82.4
4	28.1	67.9	0.125	0.875	1.50	4.99	6.49	0.46	2.04	4.99	7.49	1819	3806	5625	38.6	6.49	84.8
5	26.4	68.6	0.159	0.841	1.54	5.14	6.68	0.58	1.96	5.14	7.68	2314	3658	5972	41.1	6.68	87.3
6	24.7	69.3	0.195	0.805	1.59	5.30	6.89	0.71	1.88	5.30	7.89	2837	3502	6339	43.5	6.89	90.0
7	23.1	69.9	0.232	0.768	1.64	5.47	7.11	0.85	1.79	5.47	8.11	3376	3340	6716	46.2	7.11	92.9
8	21.5	70.5	0.271	0.729	1.69	5.64	7.33	0.99	1.70	5.64	8.33	3943	3171	7114	48.8	7.33	95.8
9	19.8	71.2	0.312	0.688	1.75	5.82	7.57	1.15	1.60	5.82	8.57	4540	2993	7533	51.7	7.57	99.0
10	18.2	71.8	0.354	0.646	1.80	6.01	7.81	1.30	1.51	6.01	8.82	5151	2810	7961	54.7	7.81	102.1
11	16.5	72.5	0.400	0.600	1.87	6.21	8.08	1.47	1.40	6.21	9.08	5820	2610	8431	57.9	8.08	105.6
12	14.8	73.2	0.447	0.553	1.93	6.42	8.35	1.64	1.29	6.42	9.35	6504	2406	8910	61.2	8.35	109.1
13	13.2	73.8	0.496	0.504	1.99	6.64	8.63	1.82	1.17	6.64	9.63	7217	2192	9409	64.7	8.63	112.8
14	11.6	74.4	0.547	0.453	2.07	6.86	8.93	2.01	1.06	6.86	9.93	7959	1971	9930	68.3	8.93	116.8
15	9.9	75.1	0.602	0.398	2.13	7.11	9.24	2.21	0.92	7.11	10.24	8759	1731	10490	72.1	9.24	120.8
16	8.3	75.7	0.658	0.342	2.21	7.35	9.57	2.42	0.80	7.35	10.57	9576	1488	11064	76.0	9.57	125.1
17	6.6	76.4	0.720	0.280	2.29	7.63	9.92	2.64	0.65	7.63	10.92	10476	1218	11694	80.4	9.92	129.7
18	5.0	77.0	0.783	0.217	2.38	7.91	10.29	2.87	0.51	7.91	11.29	11393	944	12337	84.8	10.29	134.5
19	3.3	77.7	0.852	0.148	2.47	8.21	10.68	3.13	0.34	8.21	11.68	12397	644	13041	89.6	10.68	141.2
20	1.7	78.3	0.922	0.078	2.57	8.52	11.09	3.39	0.18	8.52	12.09	13410	339	13749	94.5	11.09	145.0
21	0.0	79.0	1.000	0.000	2.67	8.87	11.54	3.67	0.00	8.87	12.54	14550	000	14550	100.0	11.54	151.0

* See Page 481 for an explanation and example of the data contained in this chart.

THE AIR REQUIREMENTS FOR COMBUSTION

EXPLANATION:

(1) $C + O_2 = CO_2$

(2) $CO_2 + C = 2CO$

For a gas analysis of 14 percent CO_2, the table shows 11.6 percent CO and 74.4 percent N_2 and the 11.6 percent CO results from the reduction of CO_2 no free oxygen being involved. It is now necessary to resort to the use of the Law of Hess which states that the result of a series of reactions is the same regardless of the intermediate steps, and thus, when (2) is added to (1) the result is

$2C + O = 2CO$

or $C + \frac{1}{2}O_2 = CO$

This reaction does not actually take place, but by the Law of Hess, its occurrence can be assumed.

The CO content of the effluent gases in the problem under consideration has been shown to be 11.6 percent and this theoretically results from the incomplete combustion of a certain amount of carbon of the coke. At the same time 14 percent CO_2 is derived from the carbon that is completely consumed initially. When 1 lb. C is burned under these conditions, the fraction burned to CO_2 is

$C_{CO_2} = 14/(14 + 11.6) = 0.547$

and the fraction burned to C_{CO} is $CO = 11.6/(14 + 11.6) = 0.453$

Consequently, the air required to form CO_2 is 0.547 × 151 = 82.6 cu. ft.

and that required to form CO 0.453 × 75.5 = 34.2 cu. ft.

The total volume of air used to burn one pound of carbon under these conditions is 116.8 cu. ft. It has been assumed that one ton of iron is being melted at a ratio of 10 to 1, therefore 200 lbs. of coke containing 90% carbon, or 180 lbs. of carbon are being burned. The total air consumption is

180 × 116.8 = 21,000 cu. ft. (approximately)

Since this volume of air at 60°F. and 29.92 in. of mercury (147.7 psi.) pressure is adequate, there is nothing to be gained by supplying more air to the cupola, for then the conditions which have been found to be successful will no longer exist.

COLOR SCALE FOR TEMPERATURES

The following color scale permits a rough approximation of high temperatures.

Color	Degrees Centigrade	Degrees Fahrenheit
Lowest visible red	475	885
Lowest visible red to dark red	475 to 650	885 to 1200
Dark red to cherry red	650 to 750	1200 to 1380
Cherry red to bright cherry red	750 to 815	1380 to 1500
Bright cherry red to orange	815 to 900	1500 to 1650
Orange to yellow	900 to 1090	1650 to 2000
Yellow to light yellow	1090 to 1315	2000 to 2400
Light yellow to white	1315 to 1540	2400 to 2800
White to dazzling white	1540 or higher	2800 or higher

USEFUL DATA ON COMBUSTION

AIR

Consists of 23% (by weight) of oxygen and 77% (by weight) of nitrogen; or by volume 20.7% oxygen and 79.3% nitrogen. One pound at 62° F. (barometer at 30 inches) occupies 13.1 cu. ft., and 56 cu. ft. at this temperature contain 1 lb. of oxygen.

OXYGEN—O

One pound at 62° F. occupies 12 cu. ft. According to Welters theory, any material burned with one pound of oxygen evolves 7,560 B.T.U.

CARBON—C

One pound requires for its complete combustion 2.2/3 lbs. of oxygen, or 11.6 lbs. air—150 cu. ft. of air, developing 20,160 B.T.U., of which 5,760 are latent, being expended in vaporizing the carbon; leaving 14,400 sensible. If perfect combustion takes place, 12,610 effective B.T.U. may be realized with the escaping flue gases at 600° F.

CARBON MONOXIDE—CO

One pound occupies 13½ cu. ft. at 62° F. requires 4-7 lb. of oxygen or 32 cu. ft. of air for its combustion and evolves 4,320 B.T.U. With perfect combustion and escaping flue gases at 600° F., 3,820 effective B.T.U. may be realized. One cu. ft. requires 2.4 cu. ft. of air for combustion and evolves 320 B.T.U.

HYDROGEN—H

One pound at 62° F. occupies 190 cu. ft., requires 8 lbs. of oxygen or 450 cu. ft. of air for its combustion and evolves 60,480 B.T.U. when burned to liquid water. 42 000 B.T.U. may be realized with flue gas at 600° F. One cu. ft. of hydrogen gas requires 2-1/3 cu. ft. of air for its combustion and evolves 324 B.T.U.

SULPHUR—S

One pound requires one pound of oxygen or 56 cu. ft. of air for its combustion and evolves 4,000 B.T.U., exclusive of the heat required for volatilization of the sulphur. With perfect combustion and flue gases at 600° F., 3,260 B.T.U. may be realized.

NATURAL GAS

One pound occupies 22 cu. ft. at 62° F. or 1,000 cu. ft. weigh 45 lbs. One cu. ft. requires 10 cu. ft. of air for its combustion and evolves about 1,000 B.T.U.

OIL (BEAUMONT)

Specific gravity .92 weights 7-2/3 lbs. per gallon. One barrel of 42 gals. weighs 322 lbs. Requires for complete combustion 15 lbs. of air per lb. of oil or 1,500 cu. ft. of air per gallon of oil. One pound gives about 20,000 B.T.U.

HEAT

Evolved by the combustion of any organic fuel, such as coal, is approximately that of its carbon plus that of as much of its hydrogen as exceeds the amount required to combine with its oxygen to form water. Pulverized coal weighs approximately 35 lbs. per cu. ft.

EXAMPLE

If a fuel consists of 87% C, 5% H and 8% O, the 8% of oxygen will be sufficient to combine with 1% of hydrogen leaving 4% of that element available for combustion. The B.T.U. to be derived from 1 lb. of this fuel will then be that corresponding to .87 lbs. of carbon plus .04 lbs. of hydrogen.

The above statements are approximately correct for the theoretical amount of air required at 62° F. with the barometer at 30 in. In practice, 10% to 20% more air should be provided because of the imperfect mixture with the fuel. Further corrections should be made for temperature in hot climates, also for pressure in high altitudes.

GRAINS OF MOISTURE PER CUBIC FOOT OF DRY AIR

Dry Bulb Temp.	Wet Bulb Temp.											
	62	63	64	65	66	67	68	69	70	71	72	73
90	2.72	3.05	3.40	3.71	4.06	4.44	4.78	5.15	5.54	5.94	6.35	6.71
91	2.60	2.92	3.28	3.62	3.95	4.32	4.66	5.08	5.41	5.80	6.21	6.61
92	2.50	2.81	3.14	3.49	3.84	4.20	4.53	4.92	5.30	5.70	6.11	6.48
93	2.37	2.70	3.04	3.36	3.72	4.08	4.45	4.80	5.18	5.56	5.98	6.36
94	2.26	2.58	2.92	3.26	3.60	3.96	4.31	4.66	5.07	5.45	5.85	6.25
95	2.13	2.46	2.80	3.15	3.48	3.84	4.19	4.55	4.95	5.36	5.73	6.12
96	2.04	2.34	2.69	3.00	3.36	3.73	4.08	4.44	4.83	5.20	5.61	6.00
97	1.91	2.22	2.56	2.90	3.25	3.60	3.94	4.32	4.70	5.09	5.50	5.87
98	1.79	2.12	2.45	2.79	3.11	3.50	3.83	4.21	4.58	4.98	5.39	5.75
99	1.69	2.00	2.32	2.68	3.01	3.38	3.72	4.08	4.46	4.85	5.26	5.64
100	1.57	1.89	2.22	2.54	2.88	3.25	3.63	3.98	4.34	4.73	5.14	5.52
101	1.45	1.76	2.11	2.44	2.78	3.14	3.50	3.84	4.24	4.60	5.01	5.40
102	1.35	1.66	1.98	2.32	2.66	3.02	3.36	3.75	4.11	4.49	4.90	5.28
103	1.22	1.54	1.88	2.21	2.52	2.91	3.26	3.62	4.00	4.39	4.80	5.16
104	1.12	1.43	1.76	2.09	2.44	2.78	3.14	3.50	3.88	4.25	4.66	5.05
105	.99	1.33	1.65	1.97	2.30	2.67	3.02	3.39	3.76	4.15	4.55	4.93
106	.89	1.19	1.54	1.86	2.22	2.56	2.92	3.26	3.65	4.02	4.42	4.81
107	.78	1.10	1.43	1.74	2.10	2.44	2.79	3.15	3.53	3.92	4.31	4.69
108	.68	.98	1.32	1.64	1.97	2.34	2.68	3.04	3.42	3.80	4.20	4.58
109	.56	.87	1.20	1.53	1.87	2.22	2.56	2.92	3.30	3.68	4.10	4.47
110	.43	.76	1.10	1.42	1.75	2.11	2.46	2.82	3.18	3.58	3.98	4.36

GRAINS OF MOISTURE PER POUND OF DRY AIR

Dry Bulb Temp.	Wet Bulb Temp.											
	62	63	64	65	66	67	68	69	70	71	72	73
90	38.0	42.7	47.6	52.0	57.0	62.3	67.2	72.5	78.0	83.9	89.8	95.1
91	36.4	41.0	46.0	50.7	55.5	60.8	65.7	71.0	76.5	82.0	88.0	93.7
92	35.0	39.4	44.2	49.0	54.0	59.1	64.0	69.5	75.0	80.6	86.5	92.0
93	33.2	38.0	42.7	47.2	52.4	57.7	62.8	68.0	73.4	78.9	84.9	90.6
94	31.8	36.2	41.0	46.0	50.8	56.0	60.9	66.0	71.8	77.3	83.3	89.0
95	30.0	34.7	39.4	44.2	49.1	54.3	59.3	64.5	70.2	75.7	81.7	87.3
96	28.7	33.0	38.0	42.5	47.6	52.8	57.8	63.0	68.7	74.0	80.0	85.7
97	27.0	31.4	36.2	41.0	46.0	51.1	56.0	61.5	67.0	72.5	78.4	84.0
98	25.3	30.0	34.7	39.6	44.2	49.7	54.5	60.0	65.3	71.0	77.0	82.4
99	24.0	28.3	33.0	38.0	42.8	48.0	53.0	58.2	63.8	69.4	75.3	80.9
100	22.2	26.8	31.6	36.1	41.1	46.3	51.7	56.8	62.1	67.8	73.7	79.3
101	20.6	25.0	30.0	34.7	39.7	44.8	50.0	55.0	60.7	66.0	72.0	77.6
102	19.0	23.6	28.2	33.0	38.0	43.1	48.1	53.7	59.0	64.5	70.5	76.0
103	17.4	22.0	26.8	31.5	36.1	41.7	46.6	52.0	57.5	63.0	69.0	74.5
104	16.0	20.4	25.2	29.9	35.0	40.0	45.0	50.2	55.9	61.3	67.3	73.0
105	14.2	19.0	23.7	28.2	33.1	38.3	43.4	48.7	54.2	59.9	65.7	71.3
106	12.8	17.1	22.0	26.7	31.8	36.9	42.0	47.0	52.7	58.2	64.0	69.7
107	11.1	15.8	20.5	25.0	30.0	35.2	40.2	45.5	51.0	56.7	62.4	68.0
108	9.7	14.0	19.0	23.6	28.4	33.7	38.7	44.0	49.4	55.0	61.0	66.5
109	8.0	12.5	17.2	22.0	27.0	32.1	37.0	42.2	47.8	53.5	59.5	65.0
110	6.2	11.0	15.8	20.5	25.3	30.5	35.7	40.8	46.2	52.0	57.8	63.4

NOTE—These values based on actual density of air at the measured condition.

GRAINS MOISTURE PER POUND DRY AIR

AND CORRESPONDING DEWCEL AND DEW POINT TEMPERATURES

Grains per lb. Dry Air	Dewcel Temp. °F.	Dew Point Temp. °F.	Grains per lb. Dry Air	Dewcel Temp. °F.	Dew Point Temp. °F.
13	72.9	16.9	45	112.9	45.4
14	75.2	18.4	46	113.7	46.0
15	77.3	19.9	47	114.5	46.5
16	79.3	21.2	48	115.2	47.1
17	81.3	22.5	49	115.9	47.6
18	83.1	23.8	50	116.7	48.2
19	84.8	24.8	55	120.2	50.7
20	86.3	25.9	60	123.6	53.0
21	87.9	27.0	65	126.8	55.2
22	89.5	28.0	70	129.7	57.2
23	90.9	28.9	75	132.5	59.1
24	92.2	29.8	80	135.0	60.3
25	93.6	30.7	85	137.5	62.5
26	94.8	31.6	90	139.9	64.1
27	96.1	32.5	95	142.1	65.6
28	97.2	33.4	100	144.3	67.1
29	98.4	34.2	105	146.3	68.5
30	99.4	35.0	110	148.1	69.8
31	100.4	35.8	115	150.0	71.0
32	101.5	36.6	120	151.8	72.3
33	102.5	37.4	125	153.7	73.5
34	103.5	38.2	130	155.4	74.7
35	104.4	38.9	135	157.0	75.8
36	105.3	39.6	140	158.5	76.8
37	106.2	40.3	145	160.0	77.8
38	107.1	41.0	150	161.5	78.8
39	108.0	41.7	155	163.0	79.8
40	108.8	42.3	160	164.5	80.7
41	109.7	43.0	165	165.8	81.6
42	110.5	43.6	170	167.2	82.5
43	111.4	44.2	175	168.5	83.3
44	112.1	44.8			

GRAINS MOISTURE PER STANDARD CU. FT. DRY AIR

At 60° F. and 29.92 Hg. atmospheric pressure, and corresponding Dewcel and Dew Point Temperatures

Grains per Cu. Ft.	Dewcel Temp. °F.	Dew Point Temp. °F.	Grains per Cu. Ft.	Dewcel Temp. °F.	Dew Point Temp. °F.
.55	55.3	5.2	5.4	130.2	57.5
.60	57.9	6.9	5.6	131.6	58.5
.65	60.1	8.4	5.8	132.9	59.4
.70	62.4	9.9	6.0	134.4	60.4
.75	64.5	11.3	6.5	137.6	62.6
.80	66.4	12.6	7.0	140.7	64.7
.85	68.2	13.8	7.5	143.5	66.6
.90	70.0	15.0	8.0	146.2	68.4
.95	71.7	16.1	8.5	148.7	70.1
1.00	73.2	17.1	9.0	151.2	71.8
1.2	78.9	20.9	9.5	153.4	73.3
1.4	83.5	24.0	10.0	155.6	74.8
1.6	87.0	26.9	10.5	157.7	76.2
1.8	91.8	29.5	11.0	159.7	77.6
2.0	95.0	31.7	11.5	161.7	78.9
2.2	98.2	34.1	12.0	163.6	80.2
2.4	100.9	36.2	12.5	165.5	81.4
2.6	103.5	38.2	13.0	167.2	82.5
2.8	105.9	40.1	13.5	169.0	83.7
3.0	108.3	41.9	14.0	170.6	84.7
3.2	110.4	43.5	14.5	172.4	85.8
3.4	112.5	45.1	15.0	174.0	86.8
3.6	114.5	46.6	16.0	177.3	88.8
3.8	116.5	48.0	17.0	180.3	90.6
4.0	118.4	49.4	18.0	183.3	92.3
4.2	120.3	50.7	19.0	186.3	94.0
4.4	122.1	51.9	20.0	189.0	95.6
4.6	123.8	53.1	22.0	193.7	98.5
4.8	125.5	54.3	24.0	201.0	101.2
5.0	127.1	55.4	26.0	202.5	103.7
5.2	128.6	56.4	28.0	204.0	106.0

SPEED AND FEED CALCULATIONS

FOR TURNING TOOLS, MILLING CUTTERS, AND OTHER ROTATING TOOLS

To Find	Having	Formula
Revolutions per Minute = R.P.M.	Cutting Speed in Feet per Minute = C.S., and Diameter of Tool in Inches (or Diameter of Piece Being Turned) = D	$\text{R.P.M.} \quad \frac{\text{C.S.} \times 12}{\text{D} \times 3.1416}$
Cutting (surface cutting) Speed in Feet per Minute = C.S.	Diameter of Tool in Inches (or Diameter of Piece Being Turned = D, and Revolutions per Minute = R.P.M.	$\text{C.S.} \quad \frac{\text{D} \times 3.1416 \times \text{R.P.M.}}{12}$
Feed per Minute in Inches = Fd.M.	Feed per Revolution in Inches = Fd.R., and Revolutions per Minute = R.P.M.	$\text{Fd.M.} = \text{Fd.R.} \times \text{R.P.M.}$
Feed per Revolution in Inches = Fd.R.	Feed per Minute in Inches = Fd.M., and Revolutions per Minute = R.P.M.	$\text{Fd.R.} \quad \frac{\text{Fd.M.}}{\text{R.P.M.}}$
Feed per Tooth = Fd.T.	Number of Teeth in Tool = T, and Feed per Revolution in Inches = Fd.R.	Fd.T. Fd.R.
Feed per Tooth = Fd.T.	Number of Teeth in Tool = T, Feed in Inches per Minute = Fd.M., and Speed in Revolutions per Minute = R.P.M.	$\text{Fd.T.} \quad \frac{\text{Fd.M.}}{\text{T} \times \text{R.P.M.}}$
Number of Cutting Teeth per Minute = T.M.	Number of Teeth in Tool = T, and Revolutions per Minute = R P M	$\text{T.M.} = \text{T} \times \text{R.P.M}$

CUTTING SPEEDS

FOR DRILLS, REAMERS, MILLING CUTTERS, TURNING TOOLS, AND TAPS

REVOLUTIONS PER MINUTE

Expressed to nearest single R.P.M. below 1000, and to nearest 10 above 1000.

Higher or intermediate speeds are easily found by multiplication or division. For 150 feet, use the 50 column and multiply by 3. For 25 feet use the 50 column and divide by 2.

Cutting Speed, Feet per Minute / Diameter of Moving or Piece, Inches	30	40	50	60	70	80	90	100	120	140	200
1/16	1830	2440	3060	3670	4280	4890	5500	6110	7330	8560	
3/32	1220	1630	2040	2440	2850	3260	3670	4070	4890	5700	8150
1/8	917	1220	1530	1830	2140	2440	2750	3060	3670	4280	6110
5/32	733	978	1220	1470	1710	1960	2200	2440	2930	3420	4890
3/16	611	815	1020	1220	1430	1630	1830	2040	2440	2850	4070
7/32	524	698	873	1050	1220	1400	1570	1750	2100	2440	3490
1/4	458	611	764	917	1070	1220	1380	1530	1830	2140	3060
5/16	367	489	611	733	856	978	1100	1220	1470	1710	2440
3/8	306	408	509	611	713	815	916	1020	1220	1430	2040
13/32	282	376	470	564	658	752	846	940	1130	1320	1880
7/16	262	349	437	524	611	699	786	874	1050	1220	1750
1/2	229	306	382	459	535	611	688	764	917	1070	1530
9/16	204	272	340	407	475	543	611	679	813	951	1360
5/8	184	245	306	367	428	489	552	612	736	857	1220
11/16	167	222	273	333	389	444	500	555	666	770	1110
3/4	153	203	254	306	357	408	458	508	610	711	1020
13/16	142	190	237	284	332	379	427	474	569	664	948
7/8	131	175	219	262	306	349	392	438	526	613	876
15/16	122	163	204	244	285	326	366	407	488	570	814
1	115	153	191	229	267	306	344	382	458	535	764
1-1/8	102	136	170	204	238	272	306	340	408	476	680
1-1/4	92	123	153	183	214	245	274	306	367	428	612
1-3/8	83	111	139	167	195	222	250	278	334	389	556
1-1/2	76	102	127	153	178	204	230	254	305	356	508
1-5/8	71	94	117	141	165	188	212	234	281	328	468
1-3/4	66	87	109	131	153	175	196	218	262	305	436
2	57	76	96	115	134	153	172	191	229	267	382
2-1/4	51	68	86	102	119	136	153	170	204	238	340
2-1/2	46	61	76	92	107	122	138	153	184	213	306
2-3/4	42	56	70	83	97	111	125	139	167	195	278
3	38	51	64	76	89	102	114	127	152	178	254
3-1/2	33	44	55	66	76	87	98	109	131	153	218
4	29	38	48	57	67	76	86	96	115	134	191
4-1/2	25	34	42	51	59	68	76	85	102	119	170
5	23	31	38	46	54	61	69	76	92	107	153
5-1/2	21	28	35	42	49	56	63	69	83	97	139
6	19	26	32	38	45	51	57	64	76	89	127
7	16	22	27	33	38	44	49	55	66	76	109
8	14	19	24	29	33	38	43	48	57	67	96
9	13	17	21	25	30	34	38	42	51	59	85
10	12	15	19	23	27	31	35	38	46	54	77
12	10	13	16	19	22	25	29	32	38	44	63

TABLE OF LABORATORY CONVERSION FACTORS

To convert from units in vertical column to units in horizontal column, multiply by factor found at intersection.

MASS	Grams	Kilograms	Ounces (avoir)	Pounds (avoir)
Grams..............		0.001	3.527×10^{-2}	2.205×10^{-3}
Kilograms...........	1000	....	35.274	2.2046
Ounces (avoir.).......	28.350	0.028350	....	0.0625
Pounds (avoir.)*......	453.59	0.45359	16.0	....
Ounces (troy or apoth.)	31.103	0.03110	1.0971	0.068571
Pounds (troy)........	373.24	0.37324	13.166	0.82286
Grains...............	0.06480	6.480×10^{-5}	2.286×10^{-3}	1.429×10^{-4}
Drams (troy)**........	3.8879	3.888×10^{-3}	0.13714	8.571×10^{-3}
Drams (avoir.).......	1.7718	1.772×10^{-3}	0.0625	3.906×10^{-3}
Tons (short)..........	9.072×10^{5}	907.19	3.200×10^{4}	2000
Tons (long)...........	1.016×10^{6}	1016.0	3.584×10^{4}	2240
Milligrams............	0.001	1×10^{-6}	3.527×10^{-5}	2.205×10^{-6}

* Mass of 27.692 cubic inches water weighed in air at 4.0°C., 760 mm. mercury pressure. **Same as British Drachm.

POWER	Watts	KW	Ft.lb./sec	Ft.lb./min.
Watts....................	....	0.001	0.73756	44.254
Kilowatts.................	1000	....	737.56	4.4254×10^{4}
Foot pounds per second.....	1.35582	0.0013558	....	60
Foot pounds per minute.....	0.022597	2.2597×10^{-5}	0.016667	....
Ergs per second............	1×10^{-7}	1×10^{-10}	7.3756×10^{-8}	4.4254×10^{-6}
BTU* per minute...........	17.580	0.017580	12.9661	777.966
Gram centimeters per sec....	9.8066×10^{-5}	9.8066×10^{-8}	7.2330×10^{-5}	4.3398×10^{-3}
Kilogram calories per minute.	69.767	.069767	51.457	3087.4
Horsepower................	745.2	0.7452	550	3.3×10^{4}
Lumens...................	0.001496	1.496×10^{-6}	1.0034×10^{-3}	6.6204×10^{-2}
Joules per second..........	1	0.001	0.73756	44.254
BTU* per hour.............	0.29292	2.9292×10^{-4}	0.21605	12.9629

* British Thermal Units.

WORK AND ENERGY	G.cal.	Kg.cal.	Ergs	Joules
Gram-Calories (mean).....		0.001	4.186×10^{7}	4.186
Kilogram-Calories.........	1000		4.186×10^{10}	4186
Ergs....................	2.3889×10^{-8}	2.3889×10^{-11}	....	1×10^{-7}
Joules..................	0.23889	2.3889×10^{-4}	1×10^{7}	....
BTU (mean).............	251.98	0.25198	1.0548×10^{10}	1054.8
Foot-Pounds.............	0.32389	3.2389×10	1.35582×10^{7}	1.35582
Kilogram-Meters..........	2.3427	2.3427×10	9.80665×10^{7}	9.80665
Liter-Atmospheres (normal)	24.206	0.024206	1.01328×10^{7}	101.328
Horsepower Hours........	6.4130×10^{5}	641.30	2.6845×10^{13}	2.6845×10^{6}
Foot-Poundals...........	0.010067	10.067	4.21402×10^{5}	.042140
Kilowatt Hours...........	8.6001×10^{5}	860.01	3.6000×10^{13}	3.6000×10^{6}
Watt Hours..............	860.01	0.86001	3.600×10^{10}	3600

TABLE OF LABORATORY CONVERSION FACTORS

To convert from units in vertical column to units in horizontal column, multiply by factor found at intersection.

MASS	Ounces (troy) ap	Pounds (troy) ap	Grains	Drams (troy) ap
Grams	3.215×10^{-2}	2.679×10^{-3}	15.432	0.25721
Kilograms	32.151	2.6792	15432	257.21
Ounces (avoir.)	0.91146	0.075955	437.5	7.2917
Pounds (avoir.)*	14.583	1.2153	7000	116.67
Ounces (troy or apoth.)	....	0.08333	480	8
Pounds (troy)	12	....	5760	96
Grains	2.083×10^{-3}	1.736×10^{-4}	....	0.01667
Drams (troy)**	0.1250	1.042×10^{-2}	60	....
Drams (avoir.)	0.056966	4.747×10^{-3}	27.344	0.45573
Tons (short)	2.917×10^{4}	2430.6	1.4×10^{7}	2.334×10^{5}
Tons (long)	3.267×10^{4}	2722.2	1.568×10^{7}	2.613×10^{5}
Milligrams	3.215×10^{-5}	2.679×10^{-6}	0.015432	2.5721×10^{-4}

* Mass of 27.692 cubic inches water weighed in air at 4.0°C., 760 mm. mercury pressure. **Same as British Drachm.

POWER	Erg/Sec	BTU/Min	G.Cm/Sec	Kg.Cal/Min
Watts	1×10^{7}	0.056896	1.0197×10^{4}	0.01433
Kilowatts	1×10^{10}	56.896	1.0197×10^{7}	14.3334
Foot pounds per second	1.3531×10^{7}	0.077124	1.3825×10^{4}	0.019433
Foot pounds per minute	2.2552×10^{5}	0.0012845	2.3042×10^{2}	3.2389×10^{-4}
Ergs per second	....	5.688×10^{-9}	1.0197×10^{-3}	1.4333×10^{-9}
BTU* per minute	1.7581×10^{8}	....	1.7926×10^{5}	0.25192
Gram centimeters per sec.	978.71	5.5796×10^{-6}	....	1.4053×10^{-6}
Kilogram calories per minute.	6.9767×10^{8}	4.0695	7.1141×10^{5}	...
Horsepower	7.452×10^{9}	42.4176	7.5988×10^{6}	10.688
Lumens	1.496×10^{4}	8.5096×10^{5}	15.2547	2.1437×10^{5}
Joules per second	1×10^{7}	0.056896	1.0197×10^{4}	0.01433
BTU* per hour	2.9292×10^{6}	0.01667	2.9869×10^{3}	4.1975×10^{-4}

* British Thermal Units.

WORK AND ENERGY	BTU	Ft.-Pd.	Kg. Meters	L-Atm
Gram-Calories (mean)	$3\,9685\times10^{-3}$	3.0874	0.42685	0.041311
Kilogram-Calories	3.9685	3087.4	426.85	41.311
Ergs	9.4805×10^{-11}	7.3756×10^{-8}	1.0197×10^{-8}	9.8689×10^{-8}
Joules	9.480×10^{-4}	0.73756	0.10197	9.869×10^{-3}
BTU (mean)	....	777.97	107.56	10.409
Foot-Pounds	1.2854×10^{-3}	....	0.13826	0.013381
Kilogram-Meters	9.2972×10^{-3}	7.2330	....	0.096782
Liter-Atmospheres (normal)	0.09607	74.735	10.333	....
Horsepower Hours	2545.0	1.9800×10^{6}	2.7374×10^{5}	26493
Foot-Poundals	3.9952×10^{-5}	0.031081	4.2972×10^{-3}	4.1589×10^{-4}
Kilowatt Hours	3413.0	2.6552×10^{6}	3.6710×10^{5}	3.5528×10^{6}
Watt Hours	3.4130	2655.3	367.10	3.5528×10^{3}

TABLE OF LABORATORY CONVERSION FACTORS

To convert from units in vertical column to units in horizontal column, multiply by factor found at intersection.

MASS	Drams (avoir)	Tons (short)	Tons (long)	Milligrams
Grams	0.5644	1.102×10^{-6}	9.842×10^{-7}	1000
Kilograms	564.38	1.102×10^{-3}	9.842×10^{-4}	1×10^{6}
Ounces (avoir.)	16.000	3.125×10^{-5}	2.790×10^{-5}	2.8353×10^{4}
Pounds (avoir.)*	256.00	5.0×10^{-4}	4.464×10^{-4}	4.5365×10^{5}
Ounces (troy or apoth.)	17.554	3.429×10^{-5}	3.061×10^{-5}	3.1104×10^{4}
Pounds (troy)	210.65	4.114×10^{-4}	3.674×10^{-4}	3.7325×10^{5}
Grains	0.03657	7.142×10^{-8}	6.377×10^{-8}	64.800
Drams (troy)**	2.1943	4.284×10^{-6}	3.826×10^{-6}	3.888×10^{3}
Drams (avoir.)	....	1.953×10^{-6}	1.744×10^{-6}	1.7717×10^{3}
Tons (short)	5.120×10^{5}	....	0.89286	9.0730×10^{8}
Tons (long)	5.734×10^{5}	1.1200	....	1.0162×10^{9}
Milligrams	5.644×10^{-4}	1.102×10^{-9}	9.842×10^{-10}	

* Mass of 27.692 cubic inches water weighed in air at 4.0°C., 760 mm. mercury pressure. **Same as British Drachm

POWER	HP	Lumens	Joules/Sec	BTU/Hr.
Watts	0.001341	668.45	1	3.41376
Kilowatts	1.3410	6.6845×10^{5}	1000	3413.76
Foot pounds per second	0.0018182	906.28	1.35582	4.6274
Foot pounds per minute	3.0303×10^{-5}	13.3456	0.022597	0.07707
Ergs per second	1.3412×10^{-10}	6.6845×10^{-5}	1×10^{-7}	4.4128×10^{-7}
BTU* per minute	0.023575	11751	17.580	60
Gram centimeters per sec.	1.3151×10^{-7}	0.065552	9.8066×10^{-5}	3.3477×10^{-4}
Kilogram calories per minute	0.093557	46636	69.767	238.1688
Horsepower	....	498129	745.2	2545.1
Lumens	2.0061×10^{-6}	....	1.496×10^{-3}	5.10689×10^{-3}
Joules per second	0.001341	668.45	....	3.41376
BTU* per hour	3.9281×10^{-4}	195.80	0.29292	

* British Thermal Units.

WORK AND ENERGY	H.P. Hours	Ft. Poundals	KWH	WH
Gram-Calories (mean)	1.5593×10^{-6}	99.334	1.1628×10^{-6}	1.1628×10^{-3}
Kilogram-Calories	1.5593×10^{-3}	99334	1.1628×10^{-3}	1.1628
Ergs	3.7251×10^{-14}	2.3730×10^{-6}	2.7777×10^{-13}	2.7777×10^{-10}
Joules	3.725×10^{-7}	23.730	2.778×10^{-7}	2.778×10^{-4}
BTU (mean)	3.9292×10^{-4}	2.5030×10^{4}	2.930×10^{-4}	0.2930
Foot-Pounds	5.0505×10^{-7}	32.174	3.7662×10^{-7}	3.7662×10^{-4}
Kilogram-Meters	3.6530×10^{-6}	232.71	2.7235×10^{-6}	2.7235×10^{-3}
Liter-Atmospheres (normal)	3.7745×10^{-5}	20404.5	2.8149×10^{-7}	2.8149×10^{-4}
Horsepower Hours	....	6.3706×10^{7}	0.7457	745.7
Foot-Poundals	1.5697×10^{-8}	....	1.1805×10^{-8}	1.1805×10^{-5}
Kilowatt Hours	1.3410	8.4709×10^{7}	....	1000
Watt Hours	1.3410×10^{-3}	8.4709×10^{4}	0.001	

TABLE OF LABORATORY CONVERSION FACTORS

VOLUME LIQUID MEASURE	Barrel (U.S.)	Cubic Centimeter	Cubic Feet	Cubic Inch
1 barrel (U.S.)	....	1.192×10^{5}	4.212	7.278×10^{3}
1 cubic centimeter	8.389×10^{-6}	....	3.533×10^{-5}	6.104×10^{-2}
1 cubic foot	2.734×10^{-1}	2.831×10^{4}	....	1728
1 cubic inch	1.374×10^{-4}	1.639×10^{1}	5.787×10^{-4}	....
1 gallon (Br.)	3.813×10^{-2}	4.546×10^{3}	1.605×10^{-1}	2.773×10^{2}
1 gallon (U.S.)	3.175×10^{-2}	3.785×10^{3}	1.337×10^{-1}	2.310×10^{2}
1 liter	8.389×10^{-3}	1.000×10^{3}	3.532×10^{-2}	6.103×10^{1}
1 milliliter	8.389×10^{-6}	1.000027	3.532×10^{-5}	6.102×10^{-2}
1 ounce (Br.)	2.383×10^{-4}	2.841×10^{1}	1.003×10^{-3}	1.734
1 ounce (U.S.)	2.480×10^{-4}	2.957×10^{1}	1.044×10^{-3}	1.805
1 pint (U.S.)	3.968×10^{-3}	4.732×10^{2}	1.671×10^{-2}	2.888×10^{1}
1 quart (U.S.)	7.937×10^{-3}	9.464×10^{2}	3.342×10^{-2}	5.775×.10

1 dram = 0.0078125 (U.S.) 1 gill = 0.25 pts. 1 minim (U.S.) = 1.3021×10^{4} pt. (U.S. fluid) 1 minim (British) = 0.059194 cu. cm.

PRESSURE MEASURE	Kg/Cm²	Lbs/In²	T/Ft²	Atm.
Kilograms per square centimeter		14.22	1.024	0.968
Pounds per square inch	7.032×10^{-2}	....	7.200×10^{-2}	6.800×10^{-2}
Tons per square foot	0.977	13.89	....	0.945
Atmosphere	1.033	14.696	1.058	
Column of Mercury at 0°C Meters	1.359	19.34	1.392	1.316
Column of Mercury at 0°C Inches	3.453×10^{-2}	0.491	3.536×10^{-2}	3.342×10^{-2}
Column of Water at 15°C Meters	9.990×10^{-2}	1.421	1.023×10^{-1}	9.671×10^{-2}
Column of Water at 15°C Inches	2.538×10^{-3}	3.610×10^{-2}	2.599×10^{-3}	2.456×10^{-3}
Column of Water at 15°C Feet	3.045×10^{-2}	4.331×10^{-1}	3.119×10^{-2}	2.947×10^{-2}
Pounds per square foot	4.883×10^{-4}	6.944×10^{-3}	5×10^{-4}	4.726×10^{-4}
Kilograms per square meter	1×10^{-4}	1.422×10^{-3}	1.024×10^{-4}	9.681×10^{-5}
Millimeters of Mercury	1.360×10^{-3}	1.933×10^{-2}	1.392×10^{-3}	1.316×10^{-3}

TABLE OF LABORATORY CONVERSION FACTORS

VOLUME LIQUID MEASURE	Gallon (Br.)	Gallon (U.S.)	Liter	Milliliter
1 barrel (U.S.)	26.23	31.50	1.192×10^{2}	1.192×10^{5}
1 cubic centimeter	2.200×10^{-4}	2.642×10^{-4}	9.999×10^{-4}	0.99997
1 cubic foot	6.229	7.481	2.832×10^{1}	2.832×10^{4}
1 cubic inch	3.598×10^{-3}	4.329×10^{-3}	1.639×10^{-2}	1.639×10^{1}
1 gallon (Br.)	....	1.201	4.546	4.546×10^{3}
1 gallon (U.S.)	8.327×10^{-1}	....	3.785	3.785×10^{3}
1 liter	2.200×10^{-1}	2.642×10^{-1}	....	1×10^{3}
1 milliliter	2.199×10^{-4}	2.642×10^{-4}	1×10^{-3}	....
1 ounce (Br.)	6.250×10^{-3}	7.500×10^{-2}	2.841×10^{-2}	2.841×10^{1}
1 ounce (U.S.)	6.505×10^{-3}	7.813×10^{-3}	2.957×10^{-2}	2.957×10^{1}
1 pint (U.S.)	2.082×10^{-1}	0.125	4.732×10^{-1}	4.732×10^{1}
1 quart (U.S.)	4.164×10^{-1}	0.250	9.463×10^{-1}	9.433×10^{2}

PRESSURE MEASURE	Column of Hg. at 0°C		Column of H_2O	
	M	In.	M	In.
Kilograms per square centimeter	0.736	2.896×10^{1}	1.001×10^{1}	3.941×10^{2}
Pounds per square inch	5.171×10^{-2}	2.036	0.704	2.770×10^{1}
Tons per square foot	0.718	2.828×10^{1}	9.773	3.848×10^{2}
Atmosphere	7.599×10^{-1}	2.992×10^{1}	1.034×10^{1}	4.071×10^{2}
Column of Mercury at 0°C Meters		3.937×10^{1}	1.361×10^{1}	5.357×10^{2}
Column of Mercury at 0°C Inches	2.540×10^{-2}		3.457×10^{-1}	1.361×10^{-1}
Column of Water at 15°C Meters	7.348×10^{-2}	2.893		3.937×10^{1}
Column of Water at 15°C Inches	1.867×10^{-3}	7.348×10^{-2}	2.540×10^{-2}	
Column of Water at 15°C Feet	2.240×10^{-2}	8.818×10^{-1}	3.048×10^{-1}	12
Pounds per square foot	3.591×10^{-4}	1.414×10^{-2}	4.887×10^{-3}	1.924×10^{-1}
Kilograms per square meter	7.353×10^{-5}	2.896×10^{-3}	1.001×10^{-3}	3.940×10^{-2}
Millimeters of Mercury	1×10^{-3}	3.937×10^{-2}	1.361×10^{-2}	5.356×10^{-1}

TABLE OF LABORATORY CONVERSION FACTORS

VOLUME LIQUID MEASURE	Ounce (Br.)	Ounce (U.S.)	Pint (U.S.)	Quart (U.S.)
1 barrel (U.S.)....	4.197×10^{3}	4.032×10^{3}	252	126
1 cubic centimeter.	3.520×10^{-2}	3.381×101^{2}	2.113×10^{-3}	1.057×10^{-3}
1 cubic foot.......	9.776×10^{2}	9.575×10^{2}	5.984×10^{1}	2.992×10^{1}
1 cubic inch.......	5.773×10^{-1}	5.541×10^{-1}	3.463×10^{-2}	1.732×10^{-2}
1 gallon (Br.).....	160	1.536×10^{2}	9.608	4.804
1 gallon (U.S.)....	1.333×10^{2}	128	8	4
1 liter............	35.196	33.815	2.113	1.057
1 milliliter........	3.520×10^{-2}	3.381×10^{-1}	2.113×10^{-3}	1.567×10^{-3}
1 ounce (Br.).....	....	9.607×10^{-1}	6.004×10^{-2}	3.002×10^{-2}
1 ounce (U.S.)....	1.041	....	6.25×10^{-2}	3.125×10^{-2}
1 pint (U.S.)......	1.665×10^{1}	16.0		0.5
1 quart (U.S.).....	3.309×10^{1}	32.0		

1 dram = 0.0078125 (U.S.) 1 gill = 0.25 pts. 1 minim (U.S.) = 1.3021×10^{4} pt.
(U.S. fluid) 1 minim (British) = 0.059194 cu. cm.

PRESSURE MEASURE	Column of H_2O Ft.	Lbs/Ft²	Kg/M²	Mm Hg
Kilograms per square centimeter.............	3.284×10^{1}	2.048×10^{3}	1×10^{4}	7.356×10^{2}
Pounds per square inch...	2.309	144	7.031×10^{2}	5.172×10^{1}
Tons per square foot......	3.206×10^{1}	2×10^{3}	9.765×10^{3}	7.183×10^{2}
Atmosphere..............	3.393×10^{1}	2.116×10^{3}	1.033×10^{4}	760
Column of Mercury at 0°C Meters................	4.464×10^{1}	2.785×10^{3}	1.360×10^{4}	1×10^{3}
Column of Mercury at 0°C Inches................	1.134	7.073×10^{1}	3.453×10^{2}	2.54×10^{1}
Column of Water at 15°C Meters................	3.281	2.046×10^{2}	9.991×10^{2}	7.349×10^{1}
Column of Water at 15°C Inches................	8.333×10^{-2}	5.198	2.538×10^{1}	1.867
Column of Water at 15°C Feet..................		6.237×10^{1}	3.045×10^{2}	2.240×10^{1}
Pounds per square foot....	1.603×10^{-2}	....	5.336	7.447×10^{3}
Kilograms per square meter	3.284×10^{-3}	1.874×10^{-1}	....	7.356×10^{-2}
Millimeters of Mercury...	4.464×10^{-2}	1.343×10^{-4}	13.59	

TABLE OF LABORATORY CONVERSION FACTORS

VOLUME DRY MEASURE	Bushel (U.S.)	Bushel (Br.)	Cubic Foot	Cubic Inch	Cubic Meter	Cubic Yard	Peck	Pint	Quart
Bushel (U.S.)...........	....	0.969	1.244	2.150×10^{3}	3.542×10^{-2}	4.609×10^{-2}	4	64	32
Bushel (Br.)............	1.032	....	1.284	2.219×10^{3}	3.637×10^{-2}	4.756×10^{-2}	4.128	66.08	33.04
Cubic Foot.............	8.036×10^{-1}	7.786×10^{-1}	....	1728	2.832×10^{-2}	3.704×10^{-2}	3.214	51.43	25.71
Cubic Inch.............	4.650×10^{-4}	4.505×10^{-4}	5.787×10^{-4}	....	1.639	2.143×10^{-5}	1.860×10^{-3}	2.976×10^{-2}	1.488×10^{-2}
Cubic Meter............	2.838×10^{1}	27.49	35.31	6.102×10^{4}	....	1.308	1.135×10^{2}	1.816×10^{3}	9.081×10^{2}
Cubic Yard.............	21.70	21.03	27	4.666×10^{4}	7.646×10^{-1}	....	86.78	1.389×10^{3}	6.943×10^{2}
Peck..................	0.25	2.422×10^{-1}	3.111×10^{-1}	5.376×10^{2}	8.810×10^{-4}	1.152×10^{-2}	....	16	8
Pint...................	1.563×10^{-2}	1.513×10^{-2}	1.944×10^{-2}	33.60	5.506×10^{-1}	7.202×10^{-4}	6.250×10^{-2}	....	.5
Quart..................	3.125×10^{-2}	$3\ 027\times10^{-2}$	3.889×10^{-2}	67.20	1.101	1.440×10^{-3}	.125	2	....

TABLE OF LABORATORY CONVERSION FACTORS

LINEAR MEASURE	Centimeters	Feet	Inches	Kilometers	Meters	Miles	Mils	Rods	Yards
Centimeter	....	3.281×10^{-2}	3.937×10^{-1}	1×10^{-5}	1×10^{-2}	6.214×10^{-6}	3.937×10^{2}	1.988×10^{-3}	1.094×10^{-2}
Foot	3.048×10^{-1}	....	12	3.048×10^{-4}	3.048×10^{-1}	1.894×10^{-4}	1.200×10^{4}	6.061×10^{-2}	3.333×10^{-1}
Inch	2.540	8.333×10^{-2}	....	2.540×10^{-5}	2.540×10^{-2}	1.578×10^{-5}	1×10^{3}	5.051×10^{-3}	2.778×10^{-2}
Kilometer	1×10^{5}	3.281×10^{3}	3.937×10^{4}	....	1×10^{3}	6.214×10^{-1}	3.937×10^{7}	1.988×10^{2}	1.094×10^{3}
Meter	1×10^{2}	3.281	39.37	1×10^{-3}	....	6.214×10^{-4}	3.937×10^{4}	1.988×10^{-1}	1.094
Mile	1.609×10^{5}	5.280×10^{3}	6.336×10^{4}	1.609	1.609×10^{3}	....	6.336×10^{7}	320	1760
Mil	2.540×10^{-3}	8.333×10^{-5}	1×10^{-3}	2.540×10^{-8}	2.540×10^{-5}	1.578×10^{-8}	....	5.051×10^{-6}	2.778×10^{-5}
Rod	5.029×10^{2}	16.5	198	5.029×10^{-3}	5.029	3.125×10^{-3}	1.980×10^{5}	....	5.5
Yard	9.144×10^{1}	3	36	9.144×10^{-4}	9.144×10^{-1}	5.682×10^{-4}	3.600×10^{4}	1.818×10^{-1}	....

TABLE OF LABORATORY CONVERSION FACTORS

AREA MEASURE	Acre	Circular mil	Square Centimeter	Square Foot
Acre		4.927×10^{12}	4.047×10^{7}	4.356×10^{4}
Circular mil	2.030×10^{-14}	....	5.067×10^{-6}	5.454×10^{-9}
Square centimeter	2.471×10^{-8}	1.974×10^{5}	....	1.076×10^{-3}
Square foot	2.296×10^{-5}	1.833×10^{8}	9.290×10^{2}	....
Square inch	1.594×10^{-7}	1.273×10^{-6}	6.452	6.944×10^{-3}
Square kilometer	2.471×10^{2}	1.974×10^{15}	1×10^{10}	1.076×10^{7}
Square meter (centares)	2.471×10^{-4}	1.974×10^{9}	1×10^{4}	1.076×10^{1}
Square mil	1.594×10^{-13}	1.2732	6.4516×10^{-6}	6.944×10^{-9}
Square mile	640	5.112×10^{15}	2.590×10^{10}	2.788×10^{7}
Square millimeter	2.470×10^{-10}	1.974×10^{3}	1×10^{-2}	1.076×10^{-5}
Square rod	6.250×10^{-3}	4.995×10^{10}	2.529×10^{5}	2.723×10^{2}
Square yard	2.066×10^{-4}	1.650×10^{9}	8.361×10^{3}	9

1 are = 1 sq. dekameter = 1076.41 sq. ft.
1 hectare = 100 ares = 107641 sq. ft. = 2.471 acres

AREA MEASURE	Square Inch	Square Kilometer	Square Meter (centares)	Square Mil
Acre	6.273×10^{6}	4.047×10^{-3}	4.047×10^{3}	6.273×10^{12}
Circular mil	7.854×10^{-7}	5.067×10^{-16}	5.067×10^{-10}	7.854×10^{-1}
Square centimeter	1.550×10^{-1}	1×10^{-10}	1×10^{-4}	1.550×10^{5}
Square foot	144	9.290×10^{-8}	9.290×10^{-2}	1.44×10^{8}
Square inch	....	6.452×10^{-10}	6.452×10^{-4}	1×10^{6}
Square kilometer	1.550×10^{9}	....	1×10^{6}	1.550×10^{15}
Square meter (centares)	1.550×10^{3}	1×10^{-6}	....	1.550×10^{9}
Square mil	1×10^{-6}	6.452×10^{-16}	6.452×10^{-10}	....
Square mile	4.014×10^{9}	2.590	2.590×10^{6}	4.014×10^{3}
Square millimeter	1.550×10^{-3}	1×10^{-12}	1×10^{-6}	1.550×10^{3}
Square rod	3.920×10^{4}	2.529×10^{-5}	2.529×10^{1}	3.920×10^{10}
Square yard	1.296×10^{3}	8.361×10^{-7}	8.361×10^{-1}	1.296×10^{9}

1 are = 1 sq. dekameter = 1076.41 sq. ft.
1 hectare = 100 ares = 107641 sq. ft. = 2.471 acres

TABLE OF LABORATORY CONVERSION FACTORS

AREA MEASURE	Square Mile	Square Millimeter	Square Rod	Square Yard
Acre......................	1.563×10^{-3}	4.047×10^{9}	160	4.840×10^{3}
Circular mil...............	1.956×10^{-16}	5.067×10^{-4}	2.002×10^{-11}	6.059×10^{-10}
Square centimeter.........	3.861×10^{-11}	1×10^{2}	3.954×10^{-6}	1.196×10^{-4}
Square foot...............	3.587×10^{-8}	9.290×10^{4}	3.673×10^{-3}	1.111×10^{-1}
Square inch...............	2.491×10^{-10}	6.452×10^{2}	2.551×10^{-5}	7.716×10^{-4}
Square kilometer..........	3.861×10^{-1}	1×10^{12}	3.954×10^{4}	1.196×10^{6}
Square meter (centares)....	3.861×10^{-7}	1×10^{6}	3.954×10^{-2}	1.196
Square mil................	2.491×10^{-16}	6.452×10^{-4}	2.551×10^{-11}	7.716×10^{-10}
Square mile..............	....	2.590×10^{12}	1.024×10^{5}	3.098×10^{6}
Square millimeter.........	3.861×10^{-13}	....	3.954×10^{4}	1.196×10^{6}
Square rod................	9.766×10^{-6}	2.529×10^{-5}	....	3.025×10^{1}
Square yard..............	3.228×10^{-7}	8.361×10^{-7}	3.306×10^{-2}	....

1 are = 1 sq. dekameter = 1076.41 sq. ft.
1 hectare = 100 ares = 107641 sq. ft. = 2.471 acres

AREAS OF SQUARE AND ROUND BARS

Size Inches	Area Square Inches		Size Inches	Area Square Inches	
	Square	Round		Square	Round
0			3	9.000	7.069
1/16	.0039	.0031	1/16	9.379	7.366
1/8	.0156	.0123	1/8	9.766	7.670
3/16	.0352	.0276	3/16	10.160	7.980
1/4	.0625	.0491	1/4	10.563	8.296
5/16	.0977	.0767	5/16	10.973	8.618
3/8	.1406	.1105	3/8	11.391	8.946
7/16	.1914	.1503	7/16	11.816	9.281
1/2	.2500	.1963	1/2	12.250	9.621
9/16	.3164	.2485	9/16	12.691	9.968
5/8	.3906	.3068	5/8	13.141	10.321
11/16	.4727	.3712	11/16	13.598	10.680
3/4	.5625	.4418	3/4	14.063	11.045
13/16	.6602	.5185	13/16	14.535	11.416
7/8	.7656	.6013	7/8	15.016	11.793
15/16	.8789	.6903	15/16	15.504	12.177
1	1.0000	.7854	4	16.000	12.566
1/16	1.1289	.8866	1/16	16.504	12.962
1/8	1.2656	.9940	1/8	17.016	13.364
3/16	1.4102	1.1075	3/16	17.535	13.772
1/4	1.5625	1.2272	1/4	18.063	14.186
5/16	1.7227	1.3530	5/16	18.598	14.607
3/8	1.8906	1.4849	3/8	19.141	15.033
7/16	2.0664	1.6230	7/16	19.691	15.466
1/2	2.2500	1.7671	1/2	20.250	15.904
9/16	2.4414	1.9175	9/16	20.816	16.349
5/8	2.6406	2.0739	5/8	21.391	16.800
11/16	2.8477	2.2365	11/16	21.973	17.257
3/4	3.0625	2.4053	3/4	22.563	17.721
13/16	3.2852	2.5802	13/16	23.160	18.190
7/8	3.5156	2.7612	7/8	23.766	18.665
15/16	3.7539	2.9483	15/16	24.379	19.147
2	4.0000	3.1416	5	25.000	19.635
1/16	4.2539	3.3410	1/16	25.629	20.129
1/8	4.5156	3.5466	1/8	26.266	20.629
3/16	4.7852	3.7583	3/16	26.190	21.135
1/4	6.0525	3.9761	1/4	27.563	21.648
5/16	5.3477	4.2000	5/16	28.223	22.166
3/8	5.6406	4.4301	3/8	28.891	22.691
7/16	5.9414	4.6664	7/16	29.566	23.221
1/2	6.2500	4.9087	1/2	30.250	23.758
9/16	6.5664	5.1572	9/16	30.941	24.301
5/8	6.8906	5.4119	5/8	31.641	24.850
11/16	7.2227	5.6727	11/16	32.348	25.406
3/4	7.5625	5.9396	3/4	33.063	25.967
13/16	7.9102	6.2126	13/16	33.785	26.535
7/8	8.2656	6.4918	7/8	34.516	27.109
15/16	8.6289	6.7771	15/16	35.254	27.688
3	9.0000	7.0686	6	36.000	28.274

AREAS OF SQUARE AND ROUND BARS

Size Inches	Area Square Inches		Size Inches	Area Square Inches	
	Square	Round		Square	Round
6	36.000	28.274	9	81.000	63.617
1/16	36.754	28.866	1/16	82.129	64.504
1/8	37.516	29.465	1/8	83.266	65.397
3/16	38.285	30.069	3/16	84.410	66.296
1/4	39.063	30.680	1/4	85.563	67.201
5/16	39.848	31.296	5/16	86.723	68.112
3/8	40.641	31.919	3/8	87.891	69.029
7/16	41.441	32.548	7/16	89.066	69.953
1/2	42.250	33.183	1/2	90.250	70.882
9/16	43.066	33.824	9/16	91.441	71.818
5/8	43.891	34.472	5/8	92.461	72.760
11/16	44.723	35.125	11/16	93.848	73.708
3/4	45.563	35.785	3/4	95.063	74.662
13/16	46.410	36.450	13/16	96.285	75.622
7/8	47.266	37.122	7/8	97.516	76.589
15/16	48.129	37.800	15/16	98.754	67.561
7	49.000	38.485	10	100.000	78.540
1/16	49.879	39.175	1/16	101.254	79.525
1/8	50.766	39.871	1/8	102.516	80.516
3/16	51.660	40.574	3/16	103.785	81.513
1/4	52.563	41.282	1/4	105.063	82.516
5/16	53.473	41.997	5/16	106.348	83.525
3/8	54.391	42.718	3/8	107.641	84.541
7/16	55.316	43.445	7/16	108.941	85.563
1/2	56.250	44.179	1/2	110.250	86.590
9/16	57.191	44.918	9/16	111.566	87.624
5/8	58.141	45.664	5/8	112.891	88.664
11/16	59.098	46.415	11/16	114.223	89.710
3/4	60.063	47.173	3/4	115.563	90.763
13/16	61.035	47.937	13/16	116.910	91.821
7/8	61.016	48.707	7/8	118.266	92.886
15/16	63.004	49.483	15/16	119.269	93.957
8	64.000	50.265	11	121.000	95.033
1/16	65.004	51.054	1/16	122.379	96.116
1/8	66.016	51.849	1/8	123.766	97.205
3/16	67.305	52.649	3/16	125.160	98.301
1/4	68.063	53.456	1/4	126.563	99.402
5/16	69.098	54.269	5/16	127.973	100.510
3/8	70.141	55.088	3/8	129.391	101.623
7/16	71.191	55.914	7/16	130.816	102.743
1/2	72.250	56.745	1/2	132.250	103.869
9/16	73.316	57.583	9/16	133.691	105.001
5/8	74.391	58.426	5/8	135.141	106.139
11/16	75.473	59.276	11/16	136.598	107.284
3/4	76.563	60.132	3/4	138.063	108.434
13/16	77.660	60.994	13/16	139.535	109.591
7/8	78.766	61.863	7/8	141.016	110.754
15/16	79.879	62.737	15/16	142.504	111.923
9	81.000	63.617	12	144.000	113.098

FACTORS FOR ESTIMATING WEIGHTS OF CASTINGS

PATTERN MATERIAL	* _Specific Gravity_	CASTING MATERIAL				
		Aluminum	Brass 70-30	Copper	Gray Iron	Magnesium
		2.81	8.53	8.96	7.20	1.80
Aluminum	_2.81_	1.00	3.04	3.19	2.56	0.64
Ash	_0.64_	4.40	13.3	14.0	11.2	2.81
Brass	_8.53_	0.33	1.00	1.05	0.85	0.21
Cast (Gray) Iron	_7.20_	0.39	1.18	1.24	1.00	0.25
Cedar	_0.35_	8.02	24.4	25.6	20.6	5.15
Cherry	_0.43_	6.54	19.8	20.8	16.7	4.19
Copper	_8.96_	0.31	0.95	1.00	0.80	0.20
Cypress	_0.47_	5.98	18.2	19.1	15.3	3.83
Mahogany	_0.71_	3.96	12.0	12.6	10.1	2.54
Maple	_0.59_	4.76	14.5	15.2	12.2	3.05
Malleable Iron	_7.35_	0.38	1.16	1.22	0.98	0.24
Oak	_0.70_	4.01	12.2	12.8	10.3	2.57
Pine, White	_0.43_	6.54	19.8	20.8	16.7	4.19
Pine, Yellow	_0.64_	4.40	13.3	14.0	11.2	2.81
Spruce	_0.45_	6.25	19.0	19.9	16.0	4.00
Steel	_7.84_	0.36	1.09	1.14	0.92	0.23
Wood's Metal	_9.73_	0.29	0.88	0.92	0.74	0.19

*Pattern materials are shown at the left of the table. Casting materials are shown at the top of the table. The factor, at the intersection of any line representing pattern material and any column representing casting material, is the ratio of casting weight to pattern weight. Pattern weight multiplied by the proper factor equals casting weight. "Example: A mahogany pattern weighs 3 ounces, or 3/16-pound (0.188-lb.). How

FACTORS FOR ESTIMATING WEIGHTS OF CASTINGS

PATTERN MATERIAL	*Specific Gravity*	CASTING MATERIAL				
		Malleable Iron	Steel Medium Carbon	Titanium	White Iron	Wood's Metal
		7.35	7.84	4.45	7.68	9.73
Aluminum	*2.81*	2.62	2.79	1.58	2.73	3.46
Ash	*0.64*	11.5	12.2	6.95	12.0	15.2
Brass	*8.53*	0.86	0.92	0.52	0.90	1.14
Cast (Gray) Iron	*7.20*	1.02	1.09	0.62	1.07	1.35
Cedar	*0.35*	21.0	22.4	12.7	22.0	27.8
Cherry	*0.43*	17.1	18.2	10.3	17.9	22.6
Copper	*8.96*	0.82	0.87	0.50	0.86	1.09
Cypress	*0.47*	15.6	16.7	9.46	16.4	20.7
Mahogany	*0.71*	10.3	11.0	6.25	10.8	13.7
Maple	*0.59*	12.5	13.3	7.54	13.0	16.5
Malleable Iron	*7.35*	1.00	1.06	0.61	1.04	1.32
Oak	*0.70*	10.5	11.2	6.35	11.0	1.39
Pine, White	*0.43*	17.1	18.2	10.3	17.9	22.6
Pine, Yellow	*0.64*	11.5	12.2	6.95	12.0	15.2
Spruce	*0.45*	16.3	17.4	9.90	17.1	21.6
Steel	*7.84*	0.94	1.00	0.57	0.98	1.24
Wood's Metal	*9.73*	0.76	0.80	0.46	0.79	1.00

much will a malleable iron casting made from it weigh? The factor found at the intersection of "Mahogany" and "Malleable Iron" is 10.3. Therefore, the casting will weigh 0.188 x 10.3; or 1.93, pounds."

Note: The foregoing is correct only in the case of solid (not hollow) patterns where the entire pattern volume is replaced by metal in the casting.

HARDNESS TESTS

Comparing Brinell hardness numbers using a 3000 kg. load,
with Rockwell B, C, D, and G scales.

BRINELL HARDNESS NUMBER		ROCKWELL HARDNESS NUMBER	
Diameter of Indentation mm.	10 mm carbide ball, 3000 kg. load, 15 sec.	B Scale 100 kg. load 1/16" ball.	C Scale 150 kg. load Diamond cone.
2.79	479	...	50.0
2.88	450	...	48.0
2.96	425	...	46.0
3.04	403	...	44.0
3.12	382	...	42.0
3.20	363	...	40.0
3.27	346	...	38.0
3.36	329	...	36.0
3.44	313	...	34.0
3.52	298	**106**	32.0
3.66	275	**104**	28.5
3.78	258	**102**	25.5
3.90	241	100	22.5
4.01	228	98	20.0
4.12	215	96	17.0
4.22	204	94	**14.5**
4.33	194	92	**12.0**
4.44	184	90	**9.0**
4.53	176	88	**6.5**
4.63	168	86	**4.0**
4.72	161	84	**2.0**
4.81	155	82	...
4.90	149	80	...
4.97	144	78	...
5.06	139	76	...
5.15	134	74	...
5.24	129	72	...
5.31	125	70	...
5.39	121	68	...
5.45	118	66	...
5.54	114	64	...
5.60	111	62	...
5.67	108	60	...
5.72	106	58	...
5.80	103	56	...

NOTE: The use of hardness scales for hardness values shown in bold face type are not recommended since they are beyond the ranges recommended for accuracy. Such values are shown for comparative purposes only. where comparisons may be desired and the recommended machine and scale are not available.

HARDNESS TESTS

Comparing Brinell hardness numbers using a 3000 kg. load, with Rockwell B, C, D, and G scales.

BRINELL HARDNESS NUMBER		ROCKWELL HARDNESS NUMBER	
Diameter of Indentation mm.	10 mm carbide ball, 3000 kg. load, 15 sec.	D Scale 100 kg. load Diamond cone.	G Scale 150 kg. load 1/16" ball.
2.79	479	63.0	. . .
2.88	450	61.5	. . .
2.96	425	60.0	. . .
3.04	403	58.5	. . .
3.12	382	57.0	. . .
3.20	363	55.5	. . .
3.27	346	54.0	. . .
3.36	329	52.5	. . .
3.44	313	50.5	. . .
3.52	298	49.5	94.0
3.66	275	46.5	91.0
3.78	258	44.5	87.5
3.90	241	42.0	84.5
4.01	228	40.0	81.5
4.12	215	38.0	78.5
4.22	204	36.0	75.5
4.33	194	34.0	72.0
4.44	184	32.0	69.0
4.53	176	30.0	65.5
4.63	168	28.0	62.5
4.72	161	26.5	59.5
4.81	155	24.5	56.5
4.90	149	22.5	53.0
4.97	144	21.0	50.0
5.06	139	**19.0**	47.0
5.15	134	**17.5**	43.5
5.24	129	**16.0**	40.5
5.31	125	**14.5**	37.5
5.39	121	**13.0**	34.5
5.45	118	**11.5**	31.0
5.54	114	**10.0**	. . .
5.60	111	**8.0**	. . .
5.67	108	. . .	. . .
5.72	106	. . .	. . .
5.80	103	. . .	. . .

NOTE: The use of hardness scales for hardness values shown in bold face type are not recommended since they are beyond the ranges recommended for accuracy. Such values are shown for comparative purposes only, where comparisons may be desired and the recommended machine and scale are not available.

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